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General Safety Standard for Installations Using Non-Medical X-Ray and Sealed Gamma-Ray Sources, Energies up to 10 MeV

AMERICAN NATIONAL STANDARD N543-1974

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[Also — E. Eisenhower
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General Safety Standard for Installations Using Non-Medical X-Ray and Sealed Gamma-Ray Sources, Energies up to 10 MeV

American National Standards
Subcommittee N43-5

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Foreword

X-ray and gamma ray sources are widely used for industrial inspection. Their utility, however, must be matched by the safety with which they are used. This Handbook of recommended safety standards, developed by American National Standards Committee N43, has been approved by ANSI as an American National Standard.

NBS has long cooperated with private organizations and with other government agencies in the establishment of voluntary standard practices. One area where NBS participation has been especially active is that concerned with the effective and safe use of ionizing radiation. As the Secretariat of Standards Committee N43, and earlier of ASA Sectional Committee Z54 which produced a standard on the same subject, the Bureau is pleased to publish and distribute this revised American National Standard.

Richard W. Roberts

RICHARD W. ROBERTS
Director

Preface

(This Preface is not a part of American National Standard N543, General Safety Standard for Installations Using Non-Medical X-Ray and Sealed Gamma Ray Sources, Energies up to 10 MeV.)

X-ray and sealed gamma-ray sources are used extensively in industry for the inspection, testing, and analysis of a wide variety of objects and materials. It is therefore essential that adequate measures be taken to protect persons who work with or are near such radiation sources, as well as the general public, against excessive exposure to radiation.

In 1946 the sectional committee of ASA issued American War Standard Z54.1-1946 "Safety Code for the Industrial Use of X-rays." Handbook 93 (Z54.1-1963), "Safety Standard for Non-Medical X-ray and Sealed Gamma-Ray Sources," issued in 1964 was a revision of a part of the war standard. These standards provided the necessary guidance for the safe installation and use of penetrating radiation equipment used in industry.

The American National Standards Committee N43 examined Z54.1 – 1963 and determined that a revision was necessary. This task was assigned to Subcommittee N43–5.

Suggestions for improvement gained in the use of this standard will be welcome. They should be sent to the American National Standards Institute, 1430 Broadway, New York, N.Y. 10018.

The American National Standards Committee N43, on Equipment for Non-Medical Radiation Application, had the following personnel at the time it processed and approved this standard:

Elmer H. Eisenhower
Chairman

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Members of Subcommittee N43–5, which had responsibility for developing this standard, are listed below.

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John P. Battema	Philips Electronic Instruments
James H. Bly	Applied Radiation Corporation
Carl B. Braestrup	Lenox Hill Hospital
H. L. Cook, Jr.	Ohmart Corporation
Howard Heffan	Naval Weapons Laboratory
Donovan Smith	U.S. Atomic Energy Commission
Major John C. Taschner	USAF Radiological Health Laboratory

Contents

AMERICAN NATIONAL STANDARD

General Safety Standard for Installations Using Non-Medical X-Ray and Sealed Gamma-Ray Sources, Energies up to 10 MeV

This standard establishes requirements for the design and operation of common types of installations which use gamma and x radiation for non-medical purposes. Its objective is to protect persons who work with or are near such installations, as well as the general public, against excessive exposure to radiation. Maximum permissible dose limits established by the National Council on Radiation Protection and Measurements are cited. Methods for achieving adequate radiation protection are described, including structural details, surveys and inspections, and operating procedures. Appendixes contain technical information useful for design of radiation shielding barriers.

Key words: Gamma-ray equipment; radiation installations; radiation safety; x-ray equipment.

1. Scope

1.1. This standard is intended to serve as a guide toward the safe use of X-ray and sealed gamma-ray sources for non-medical purposes. Its main objectives are to reduce needless exposure of persons to radiation and to ensure that no one receives more than the maximum permissible dose equivalent. These objectives are achieved by the use of appropriate equipment, ample shielding and safe operating procedures.

1.2. Those recommendations containing the word "shall" identify requirements that are necessary to meet the standards of protection of this document. Those using the word "should" indicate advisory recommendations that are to be applied when practicable.

2. Definitions

The definitions and terms contained in this standard, or in other American National Standards referred to in this document, are not intended to embrace all legitimate meanings of the terms. They are applicable only to the subject treated in this standard.

An asterisk (*) denotes those definitions taken from ANSI N1.1–1967, Glossary of Terms in Nuclear Science and Technology.

ACTIVITY (A). The quotient of *dN* by *dt*, where *dN* is the number of spontaneous nuclear transformations which occur in a quantity of a radioactive nuclide in the time interval *dt*. The special unit of activity is the curie.

*ATTENUATION. The reduction of a radiation quantity upon passage of radiation through matter, resulting from all types of interaction with that matter. The radiation quantity may be, for example, the particle flux density.

BARRIER. (See Shielding Barrier)

***CONTROLLED AREA.** A specified area in which exposure of personnel to radiation or radioactive material is controlled and which is under the supervision of a person who has knowledge of the appropriate radiation protection practices, including pertinent regulations, and who has responsibility for applying them.

CURIE (Ci). The special unit of activity. One curie equals 3.7×10^{10} spontaneous nuclear transformations per second exactly, or by popular usage, the quantity of any radioactive material having an activity of one curie.

***DOSE, ABSORBED.** The energy imparted to matter in a volume element by ionizing radiation divided by the mass of irradiated material in that volume element. The special unit of absorbed dose is the rad. One rad equals 100 ergs per gram (also commonly called dose).

***DOSE DISTRIBUTION FACTOR (DF).** A factor used in computing dose equivalent to account for the nonuniform distribution of internally deposited radionuclides.

***DOSE EQUIVALENT (H).** The product of absorbed dose, quality factor, dose distribution factor, and other modifying factors necessary to express on a common scale, for all ionizing radiations, the irradiation incurred by exposed persons. The special unit of dose equivalent is the rem. (For radiation protection purposes in this standard, the dose equivalent in rems may be considered numerically equivalent to the absorbed dose in rads and the exposure in roentgens.)

***EXPOSURE.** A measure of the ionization produced in air by x- or gamma-radiation. It is the sum of the electrical charges on all of the ions of one sign produced in air when all electrons liberated by photons in a volume element of air are completely stopped in the air, divided by the mass of the air in the volume element. The special unit of exposure is the roentgen.

***EXPOSURE RATE.** Exposure per unit time.

FAIL-SAFE DESIGN. One in which all failures of indicator or safety components that can reasonably be anticipated cause the equipment to fail in a mode such that personnel are safe from exposure to radiation. For example: (a) if a light indicating "x-rays on" fails, the production of x-rays shall be prevented, and (b) if a shutter status indicator fails, the shutter shall close.

HALF-VALUE LAYER (HVL): HALF-VALUE THICKNESS. The thickness of a specified substance which, when introduced into the path of a given beam of radiation, reduces the value of a specified radiation quantity upon transmission through the substance by one-half. It is sometimes expressed in terms of mass per unit area.

INSTALLATION. A radiation source, with its associated equipment, and the space in which it is located. (See sec. 3. Classification of Installation.)

INTERLOCK. A device for precluding access to an area of radiation hazard either by preventing entry or by automatically removing the hazard.

LEAD EQUIVALENT. The thickness of lead affording the same attenuation, under specified conditions, as the material in question.

LEAKAGE. The undesired release of radioactive material from a sealed source.

LEAKAGE RADIATION. (See Radiation, Ionizing.)

LEAK TEST. A method capable of detecting the leakage of radioactive material from a sealed source.

MAXIMUM PERMISSIBLE DOSE EQUIVALENT (MPD). The maximum dose equivalent that the body of a person or specific parts thereof shall be permitted to receive in a stated period of time. For the radiations considered here, the dose equivalent in rems may be considered numerically equal to the absorbed dose in rads and the exposure in roentgens. (See table 1.)

***MONITORING, RADIATION (RADIATION PROTECTION).** The continuing collection and assessment of the pertinent information to determine the adequacy of radiation protection practices and to alert to potentially significant changes in conditions or protection performance.

OCCUPANCY FACTOR (T). The factor by which the workload should be multiplied to correct for the degree or type of occupancy of the area in question.

OCCUPIED AREA. An area that may be occupied by persons.

QUALIFIED EXPERT. A person having the knowledge and training necessary to measure ionizing radiations and to advise regarding radiation protection, for example, persons certified in this field by the American Boards of Radiology, Health Physics, or Industrial Hygiene.

QUALITY FACTOR (Q). The linear-energy-transfer-dependent factor by which absorbed doses are to be multiplied to obtain, for radiation protection purposes, a quantity that expresses on a common scale for all ionizing radiations the irradiation incurred by exposed persons.

RADIATION PROTECTION SUPERVISOR. A person directly responsible for radiation protection. It is his duty to insure that all procedures are carried out in compliance with pertinent established rules, including recommendations contained in this document.

RADIATION PROTECTION SURVEY. Evaluation of the radiation hazards in and around an installation. It customarily includes a physical survey of the arrangement and use of the equipment and measurements of the exposure rates under expected operating conditions.

* **RADIATION, IONIZING.** Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, by interaction with matter.

PRIMARY RADIATION.

a. **X-RAYS.** Radiation coming directly from the target of the x-ray tube.

b. **BETA AND GAMMA RAYS.** Radiation coming directly from the radioactive source.

SECONDARY RADIATION. Radiation other than the primary radiation, emitted by irradiated matter.

SCATTERED RADIATION. Radiation that, during passage through matter, has been deviated in direction and usually has also had its energy diminished.

USEFUL BEAM. That part of the primary and secondary radiation which passes through the aperture, cone or other device for collimation.

LEAKAGE RADIATION. All radiation, except the useful beam, coming from the tube or source housing.

STRAY RADIATION. Radiation other than the useful beam. It includes leakage, secondary, and scattered radiation.

* **RAD.** The special unit of absorbed dose. 1 rad is 100 ergs/g.

* **RADIATION SOURCE.** An apparatus or a material emitting or capable of emitting ionizing radiation.

RADIATION WORKER. An individual whose work is normally performed in a controlled area, or whose duties involve exposure to radiation and who is subject to appropriate radiation protection controls.

* **REM.** The special unit of dose equivalent. The dose equivalent in rems is numerically equal to the absorbed dose in rads multiplied by the quality factor, the distribution factor, and any other necessary modifying factors.

RHM (Rhm). Roentgens per hour at 1 meter from the effective center of the source. (This distance is usually measured to the nearest surface of the source as its effective center generally is not known.)

* **ROENTGEN (R).** The special unit of exposure. One roentgen equals 2.58×10^{-4} Coulomb per kilogram of air.

SEALED SOURCE. Radioactive material sealed in a container or having a bonded cover, where the container or cover has sufficient mechanical strength to prevent contact with and dispersion of the radioactive material under the conditions of use and wear for which it was designed.

SCATTERED RADIATION. (See Radiation, Ionizing.)

SECONDARY RADIATION. (See Radiation, Ionizing.)

SHALL. Indicates a recommendation that is necessary or essential to meet the standards of protection of this document.

SHIELDING BARRIER. Barrier of attenuating material used to reduce radiation hazards.

SHIELDING BARRIER, PRIMARY. Barrier sufficient to attenuate the useful beam to the required level.

SHIELDING BARRIER, SECONDARY. Barrier sufficient to attenuate stray radiation to the required level.

SHOULD. Is recommended, is advisable, indicates an advisory recommendation that is to be applied when practicable.

SOURCE HOUSING. An enclosure for a sealed source which provides attenuation of the radiation emitted by the source. The enclosure may have an aperture through which the useful beam is emitted or through which the source is extracted.

STRAY RADIATION. (See Radiation, Ionizing.)

SURVEY. (See Radiation Protection Survey)

***TENTH-VALUE LAYER (TVL).** Thickness of an absorber required to attenuate a beam of radiation by a factor of ten.

TUBE HOUSING. An enclosure which contains an x-ray tube and which has a port through which the useful beam is emitted. The tube housing may also contain transformers and other appropriate components. (See appendix C for a definition of protective tube housing.)

USE FACTOR (U). The fraction of the workload during which the useful beam is pointed in the direction under consideration.

USEFUL BEAM. (See Radiation, Ionizing.)

WORKLOAD. A measure in suitable units of the amount of use of radiation equipment. For the purpose of this standard the workload is expressed in milliampere-minutes per week for x-ray sources and roentgens per week at one meter from the source for gamma-ray sources and high energy equipment (such as linear accelerators, betatrons, etc.).

3. Classification of Installations

Basically any installation which is so constructed and operated as to meet the Maximum Permissible Dose Equivalent requirements is acceptable. However, if this were the only requisite, the assumptions as to the use of the equipment and degree of occupancy might be subject to widely divergent interpretations. In order to ensure certain minimum standards of protection without needless expenditures, it has been found advisable to classify installations. Their basic requirements are given below. (See sec. 4 for selection of class, 7.6 for specific tests, and sec. 8 for operating limitations.)

3.1. **PROTECTIVE INSTALLATION.** An installation shall be so classified when it conforms with all of the following requirements:

3.1.1. The source and all objects exposed thereto are within a permanent enclosure, within which no person is permitted to remain during irradiation.

3.1.2. Reliable safety interlocks are provided to prevent access to the enclosure during irradiation (See paragraph 6.5.2).

3.1.3. If the enclosure is of such a size or is so arranged that the operator cannot readily determine whether the enclosure is unoccupied, there shall be provided:

3.1.3.1. Fail safe audible or visible warning signals (preferably of the rotating beacon type) within the enclosure which shall be actuated a minimum of 20 seconds before irradiation can be started, and the visible signal shall remain actuated during irradiation.

The audible signal shall be of a frequency or capable of producing a sound pressure level such that it can be heard over background noise that may be present. Specifications for audible signals are recommended in ANSI N2.3–1967.

3.1.3.2. Suitable means of exit, so that any person who accidentally may be shut in can leave the enclosure without delay.

3.1.3.3. Effective means within the enclosure for preventing or quickly interrupting the irradiation. The use and function of such a device shall be clearly labeled.

3.1.4. The exposure at any accessible region 2 in (5 cm) from the outside surface of the enclosure cannot exceed 0.5 mR in any 1 hour. (The distance 2 in is chosen as being the minimum practical distance from the barrier at which the exposure may be measured. The limit of 0.5 mR in 1 hour assures with reasonable probability that under practical conditions of occupancy and use, the requirements of paragraph 3.1.6 would be met.)

3.1.5. All installations shall display suitable warning signs as given below:

3.1.5.1. The interior of the exposure room shall be posted with a sign that operates in conjunction with the warning signals in paragraph 3.1.3.1. The sign shall contain the radiation symbol (see fig. 1) and the words "Danger: High Radiation Area."[1] The interior of a cabinet installation shall be posted with a similar sign which shall be visible with the access door open.

3.1.5.2. The entrance to the exposure room shall be posted with a sign containing the radiation symbol and the words "Caution: Entering Radiation Exposure Room." Cabinet type installations housing x-ray equipment shall have a sign on the outside showing the radiation symbol and "Caution: X-Rays." Cabinet type installations having a radioactive source shall have a similar sign but with the words "Caution: Radioactive Material."

3.1.6. No person, either within the controlled area or in the environs of the installation, is exposed to more than the maximum permissible dose equivalent (MPD). (See table 1.)

3.1.7. Most installations are subject to Federal, state or local regulations which may involve registration, licensing or compliance with specific rules. For example, to meet Federal requirements (AEC) the radiation levels in a noncontrolled area must not result in an exposure to an individual continuously present in the area in excess of 2 mR in any 1 hour or 100 mR in any 7 consecutive days.

3.2. **ENCLOSED INSTALLATION.** An installation shall be so classified when it conforms with all the following requirements:

3.2.1. The source and all objects exposed thereto are within a permanent enclosure, within which no person is permitted to remain during irradiation.

3.2.2. Reliable safety interlocks are provided to prevent access to the enclosure during irradiation (See paragraph 6.5.2).

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[1] Or "Caution: High Radiation Area."

TABLE 1. *Maximum permissible dose equivalent values* (*MPD*) [*21*]

Exposure of patients for medical and dental purposes is not included in the maximum permissible dose equivalent.

	Maximum 13-week dose rem [a]	Maximum yearly dose rem [a]	Maximum accumulated dose rem [a]
Controlled Areas			
Whole Body, Gonads, Lens of Eye, Red Bone Marrow	3	5	$5(N-18)$[b]
Skin (Other than hands and forearms)		15	
Hands	25	75	
Forearms	10	30	
Other Organs	5	15	
Noncontrolled Areas		0.5	

[a] The numerical value of the dose equivalent in rems may be assumed to be equal to the numerical value of the exposure in roentgens for the purpose of this report.

[b] N = Age in years and is greater than 18. When the previous occupational history of an individual is not definitely known, it shall be assumed that he has already received the MPD permitted by the formula $5(N-18)$.

3.2.3. If the enclosure is of such a size or is so arranged that the operator cannot readily determine whether the enclosure is unoccupied, there shall be provided:

3.2.3.1. Fail safe audible or visible warning signals (preferably of the rotating beacon type) within the enclosure which shall be actuated a minimum of 20 seconds before irradiation can be started, and the visible signal shall remain actuated during irradiation.

The audible signal shall be of a frequency or capable of producing a sound pressure level such that it can be heard over background noise that may be present. Specifications for audible signals are recommended in ANSI N2.3–1967.

3.2.3.2. Suitable means of exit, so that any person who accidentally may be shut in can leave the enclosure without delay.

3.2.3.3. Effective means within the enclosure for preventing or quickly interrupting the irradiation. The use and function of such a device shall be clearly labeled.

3.2.4. The exposure at any accessible and occupied area 1 foot (30 cm) from the outside surface of the enclosure does not exceed 10 mR in any 1 hour and the exposure at any accessible and normally unoccupied area 1 foot (30 cm) from the outside surface of the enclosure does not exceed 100 mR in any 1 hour. For x-ray installations, this exposure limitation shall be met for any x-ray tube to be used in the enclosures and operating at any specified mA and kV rating within the manufacturer's published recommendations. No beam limiting device or filter shall be used during these tests unless such devices and filters are permanently attached to the x-ray tubes or gamma exposure device and the unit cannot be operated without their use. The radiation source and beam direction shall be positioned and oriented so that the highest exposure rate will be encountered in the area under test provided that such positioning and orientation will serve a practical purpose in normal usage. It is assumed that under normal and practical conditions, the provisions of paragraph 3.2.6 can be met.

3.2.5. The posting requirements as listed in paragraph 3.1.5 shall be met in addition to those given below.

3.2.5.1. The accessible area in which exposure exceeds 5 mR in any 1 hour shall have signs posted showing the radiation symbol and the words "Caution: Radiation Area."

3.1.5.2. All entrances to a radiation area shall have signs posted showing the radiation symbol and the words "Caution: Entering Radiation Area."

3.2.6. No person, either within the controlled area or in the environs of the installation, is exposed to more than the maximum permissible dose equivalent (MPD). (See table 1.)

3.2.7. For Federal, state or local regulations see paragraph 3.1.7.

3.3. **UNATTENDED INSTALLATION.** An installation shall be so classified when it conforms with all of the following requirements.

3.3.1. The source is installed in a single purpose device.

3.3.2. The radioactive source is contained in a shielded enclosure. If the device is equipped with a shutter, or other absorber, so that the useful radiation beam can be reduced in magnitude, the "closed" and "open" positions shall be easily identified. X-ray machines shall have a visual warning signal when x-rays are produced.

3.3.3. Unless licensed by Federal or state authorities, the exposure at any accessible region 1 foot (30 cm) from the outside surface of the device shall not exceed 2 mR in any 1 hour when the device is in its normal operating condition, and occupancy in the vicinity of the device shall be limited so that the exposure to an individual in any one year shall not exceed 0.5 R.

3.3.4. All installations shall display a suitable warning sign as given below.

Devices utilizing a radioactive source shall be posted with the radiation symbol in figure 1 and the words "Caution: Radioactive Material." Similarly, devices housing an x-ray machine shall have the radiation symbol and the words "Caution: X-rays."

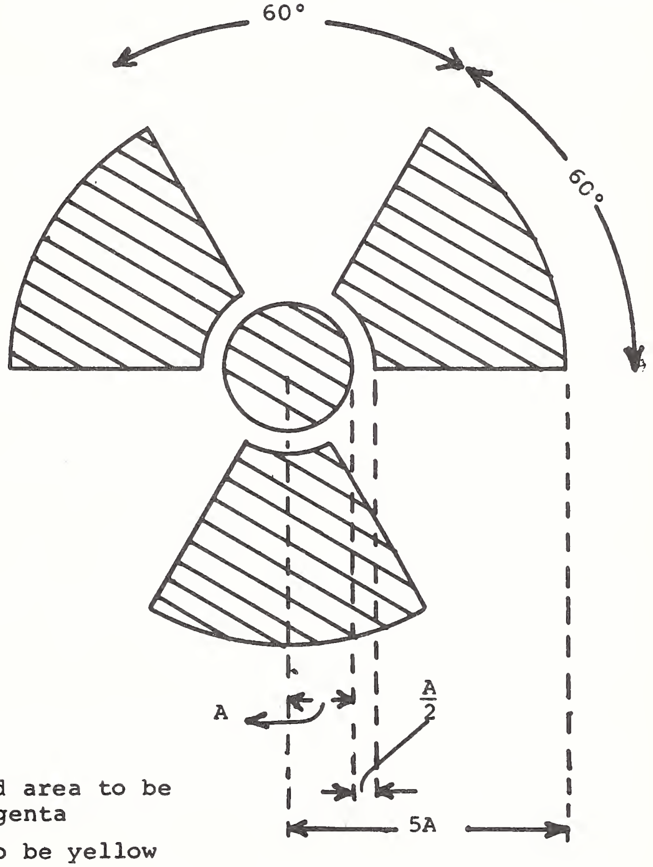
3.3.5. Service doors to areas with exposure levels exceeding that specified in paragraph 3.3.3 shall be locked or secured with fasteners requiring special tools available only to qualified service personnel.

3.3.6. For Federal, state, or local regulations, see paragraph 3.1.7.

3.4. **OPEN INSTALLATION.** An Open Installation is one which, due to operational requirements, cannot be provided with the inherent degree of protection specified for either Protective, Enclosed, or Unattended Installations. An installation shall be so classified when it conforms with all of the following requirements:

3.4.1. The source and all objects exposed thereto are within a conspicuously posted perimeter that limits the area in which the exposure can exceed 100 mR in any 1 hour. The sign shall display the radiation symbol and the words "Danger: High Radiation Area." (See footnote 1.)

3.4.2. No person has access to the high radiation area within the perimeter nor may remain in the area during irradiation. Positive means for preventing access, such as locked enclosure, shall be provided during periods of unattended irradiation.



Cross-hatched area to be purple or magenta

Background to be yellow

FIGURE 1. *Radiation symbol**

* (As specified in American National Standard N2.1-1969.)

3.4.3. The perimeter of any area in which the radiation level is in excess of 5 mR in any 1 hour shall be defined and posted with a sign displaying the radiation symbol and the words "Caution: Radiation Area."

3.4.4. The source and equipment essential to the use of the source shall be inaccessible to unauthorized use, tampering or removal. This shall be accomplished by the attendance of a knowledgeable person or by other positive means such as locked enclosure.

3.4.5. No person, either within a controlled area or in the environs of the installation, is exposed to more than the applicable maximum permissible dose equivalent (MPD). (See table 1.)

3.4.6. For Federal, state, or local regulations, see paragraph 3.1.7.

4. Selection of Class of Installation

Radiation facilities shall be constructed to meet the requirements of one of the four classes of installations described in section 3. The classes differ in their relative dependence on inherent shielding, operating restrictions, and supervision to secure the required degree of protection.

Each class has certain advantages and limitations; these are indicated below:

4.1. **PROTECTIVE INSTALLATION.** This class provides the highest degree of inherent safety because the protection does not depend on compliance with any operating limitations. This type also has the advantage of not requiring restrictions in occupancy outside the enclosure since the built-in shielding is generally sufficient to meet the maximum permissible dose requirements for noncontrolled areas.

However, the low allowable exposure level (0.5 mR in 1 hour) for this class of installation necessitates a higher degree of inherent shielding. For radiation sources of lower energies, and for smaller enclosures, such as cabinets, the initial extra cost of the increased shielding is usually insignificant compared with the operational advantages.

At higher energies, as in the megavolt region with high workloads, the required additional shielding will usually make the use of this class extremely expensive compared with the Enclosed Installation. For instance, in the case of cobalt 60, the required concrete thickness of the primary barrier for the Protective type may have to be about a foot greater than for the Enclosed type.

4.2. **ENCLOSED INSTALLATION.** This class usually offers the greatest advantages for fixed installations with low use and occupancy factors. This is particularly true for high-energy sources where the reduction in shielding may result in significant savings. The shielding requirements are considerably lower than for the Protective Installation, as much as 4.3 HVL less, yet, the inherent protection is such that the possibility of significant exposure is remote. With proper supervision, this class offers a degree of protection similar to the Protective Installation.

4.3. **UNATTENDED INSTALLATION.** This class consists of automatic equipment designed and manufactured by a supplier for a specific purpose and does not require personnel in attendance for its operation. The inherent radiation safety of such equipment makes installation possible in a noncontrolled area.

4.4. **OPEN INSTALLATION.** This class shall be selected only if operational requirements prevent the use of one of the other classes. Its use should be limited mainly to mobile and portable equipment where fixed shielding cannot be used.

The operational requirements of other classes of installations may necessitate use of this class.

The protection of personnel and the public depends almost entirely on strict adherence to safe operating procedures. With this adherence, Open Installations can provide a degree of protection similar to the other classes.

5. Plans for Radiation Installations

5.1. **REVIEW BY QUALIFIED EXPERT.** The structural shielding requirements of any new installation, or of an existing one in which changes are contemplated, should be reviewed by a qualified expert early in the planning stage.

5.2. **INFORMATION TO BE SUPPLIED TO A QUALIFIED EXPERT.** The expert should be provided with available data concerning the type of source, the kilovoltage or energy, milliamperage or output in Rhm, the contemplated use of the source, the expected workload, and use factors, the structural details of the building and the type of occupancy of all areas which might be affected by the installation.

Data for the determination of shielding barrier thicknesses may be found in the appendices of this standard. See section 6 for structural details.

5.3. **APPROVAL OF PLANS BY QUALIFIED EXPERT.** Final shielding plans and all pertinent specifications should be approved by a qualified expert before construction begins.

5.4. **EFFECT OF DISTANCE ON SHIELDING REQUIREMENTS.** Shielding requirements generally may be reduced by locating the installation at a distance from occupied areas. (See tables 7, 9, and 10 appendices B and C for minimum safe distances.)

5.5. **DIRECTION OF USEFUL BEAM.** The cost of shielding may be reduced significantly by arranging the installation so that the useful beam is directed toward occupied areas as little as possible. (There is, of course, no objection to directing the useful beam at occupied areas provided there is adequate protection.)

5.6. **CROSS SECTION OF BEAM.** Devices which permanently restrict the direction and cross section of the useful beam may reduce the area requiring primary shielding barriers.

5.7. **MULTIPLE SOURCES OF RADIATION.** Where persons are likely to be exposed to radiation from more than one source simultaneously, or at different times, the protection associated with each source shall be increased so that the total dose received by any one person from all sources shall not exceed the maximum permissible dose.

5.8. **RADIATION ENERGY, OUTPUT, AND WORKLOAD.** The shielding for each occupied area should be determined on the basis of the expected maximum kilovoltage or energy, mA or Rhm, workload, use factor, and occupancy factor associated with the area. Consideration should be given to the possibility that these may increase in the future resulting in increased exposure. It may be more economical to provide a higher degree of protection initially than to add shielding later.

6. Structural Details of Shielding Barriers

Any material will provide the required degree of shielding, if of sufficient thickness. At lower radiation energies, materials of high atomic number provide the attenuation with the least barrier weight.

6.1. **QUALITY OF SHIELDING MATERIAL.** All shielding materials shall be of assured quality, uniformity, and permanency.

6.2. **LEAD BARRIERS.**

6.2.1. Lead barriers shall be mounted in such a manner that they will not cold-flow because of their own weight and shall be protected against mechanical damage.

6.2.2. Lead sheets at joints should be in contact with a lap of at least one-half inch or twice the thickness of the sheet, whichever is the greater.

6.2.3. Welded or burned lead seams are permissible, provided the lead equivalent of the seams is not less than the minimum requirement.

6.3. **JOINTS BETWEEN DIFFERENT MATERIALS OR STRUCTURES.**

6.3.1. Joints between different kinds of shielding materials shall be constructed so that the overall protection of the barrier is not impaired.

6.3.2. Joints at the floor and ceiling shall be constructed so that the overall protection is not impaired. (See fig. 2 for example.)

6.4. **SHIELDING OF OPENINGS IN SHIELDING BARRIERS.** In the planning of an installation, careful consideration should be given to reducing the number and size of all perforations of shielding barriers and openings into protected areas. protection for all such openings shall be provided by means of suitable shielding baffles.

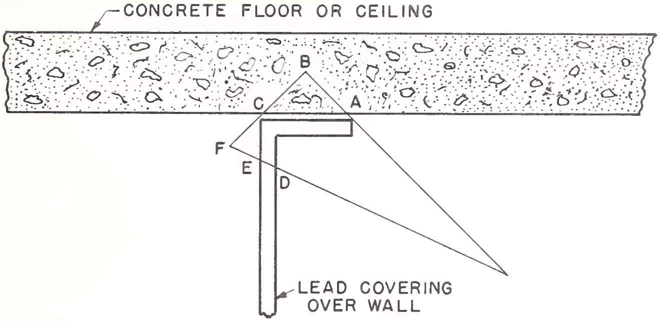


FIGURE 2. *Example of a wall joint.*

The sum of radiations through all paths *ABCF* and *DEF* to the point *F* shall be not more than the maximum permissible exposure. The framework supporting the lead wall is here considered to be of relatively x-ray transparent material.

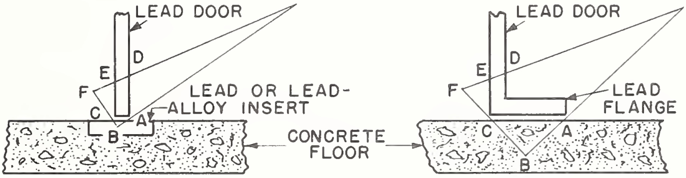


FIGURE 3. *Example of door baffle.*

The sum of radiations through all paths *ABCF* and *DEF* to the point *F* shall not be more than the maximum permissible exposure. The supporting structure for the lead door is here considered to be a framework of relatively x-ray transparent material.

6.4.1. **PERFORATIONS.** Provision shall be made to ensure that nails, rivets, or screws which perforate shielding barriers are covered to give protection equivalent to that of the unperforated barrier.

6.4.2. **OPENINGS FOR PIPES, DUCTS, CONDUITS, LOUVERS, ETC.** Holes in barriers for pipes, ducts, conduits, louvers, etc., shall be provided with baffles to ensure that the overall protection afforded by the barrier is not impaired. These holes should be located outside the range of possible orientations of the useful beam.

6.4.3. **DOORS AND OBSERVATION WINDOWS.** The lead equivalent of doors and observation windows of exposure rooms, cubicles, and cabinets shall not be less than that required for the walls or barrier in which they are located.

6.5. GENERAL PROTECTION REQUIREMENTS FOR DOORS INTO PROTECTED AREAS.

6.5.1. **LOCATION OF DOORS.** Where practical, doors into exposure rooms should be so located that the operator has direct control of access to the room.

6.5.2. **INTERLOCK SYSTEMS FOR DOORS.** All doors and panels opening into an x-ray exposure room or cabinet (except those panels which can be opened or removed only with tools) shall be provided with fail-safe interlocking switches or devices preventing irradiation unless the door or panel is closed. All doors and panels opening into a high radiation area of a gamma ray installation (except those which can be opened or removed only with tools) shall be equipped with a fail-safe device which shall either cause the level of radiation to be reduced below 100 mR in any hour upon entry into the area or shall cause a visual or audible alarm signal to energize. For temporary exposure rooms (less than 30 days) this device is not required but the door shall be equipped with a suitable lock.

6.5.3. **RESUMPTION OF OPERATION.** If the operation of any radiation source has been interrupted by the opening of a door or panel to an installation, it shall not be possible to resume operation by merely closing the door or panel in question. To resume operation, it shall be necessary, in addition, to reenergize manually a suitable device located on or near the control panel.

6.5.4. **THRESHOLD BAFFLE FOR DOOR SILL.** A door baffle or threshold may be required for installations operating above 125 kVp, if the discontinuity can be struck by the useful beam. (See figure 3 for example that fulfills the baffle requirement.)

6.5.5. **LAP OF DOOR JAMB.** The shielding lead covering of any door leading to an exposure room or cabinet shall overlap that of the door jamb and lintel so as to reduce the radiation passing through clearance spaces to the allowable limit for the door itself.

7. Radiation Protection Surveys and Inspections

7.1. **SURVEY OF NEW INSTALLATIONS.** Before a new installation is placed in routine operation a radiation protection survey shall be made by a qualified expert. This survey should determine that a leak test on sealed sources has been conducted.

7.2. **CHANGES IN EXISTING INSTALLATIONS.** A radiation protection resurvey or reevaluation by a qualified expert shall be made when changes have been made in shielding, operation, equipment, or occupancy of adjacent areas, and these changes may have adversely affected radiation protection. A qualified expert should be consulted in case of doubt.

7.3. **REPORT OF RADIATION PROTECTION SURVEY.** No existing installation shall be assumed to conform with the provisions of this standard unless a radiation protection survey has been made by a qualified expert and a report of the survey has been placed on file at the installation.

7.4. **ELIMINATION OF HAZARDS.** The radiation hazards that may be found in the course of a survey shall be eliminated before the installation is used.

7.5. **RETENTION OF SURVEY REPORTS.** Reports of all radiation protection surveys shall be retained together with a record of the action taken with respect to the recommendations they contain.

7.6. **RADIATION PROTECTION SURVEY PROCEDURES.** A radiation protection survey shall include the following procedures:

7.6.1. **INSTALLATION INSPECTION.** The installation shall be inspected to verify or determine the present and expected occupancy of the adjacent areas. Devices that have a bearing on radiation protection shall be inspected for proper operation. These include audible or visible warning signals, interlocks, delay switches, and mechanical or electrical devices which restrict positioning of the radiation source.

7.6.2. **RADIATION MEASUREMENTS.** Radiation exposure shall be measured in all adjacent areas that can be occupied. The measurements shall be made under practical conditions of operation that will result in the greatest exposure at the point of interest. X-ray apparatus should be operated at the maximum kilovoltage and at its maximum milliamperage for continuous operation at that voltage. High energy equipment (such as linear accelerators, betatrons, etc.) should be operated at maximum radiation output.

7.6.3. **PERSONNEL MONITORING.** A qualified expert shall determine the adequacy of the personnel monitoring programs for all classes of installations. Personnel monitoring may not be required for a Protective Installation where a person cannot enter the exposure cubicle.

7.6.4. **CONTENTS OF RADIATION PROTECTION SURVEY REPORT.** A report of a radiation protection survey shall include:

7.6.4.1. Identification of the persons conducting the survey and the date of survey.

7.6.4.2. Identification of the radiation source and installation by suitable means, e.g., serial number, room number, and building number or name.

7.6.4.3. Identification of instrument used and date of last calibration.

7.6.4.4. The identity and Rhm or activity in curies of a gamma source, including calibration date, or the potential and current at which an x-ray tube was operated during the test.

7.6.4.5. A statement indicating the appropriate classification of the installation.

(The following shall be included when applicable.)

7.6.4.6. The location of the source and the orientation of the useful beam with relation to each exposure measurement.

7.6.4.7. Exposure rates in all adjacent occupied areas. The locations of the measurements shall be suitably identified; appropriate drawings may facilitate this identification.

7.6.4.8. A description of the existing mechanical and electrical limiting devices that restrict the orientation of the useful beam and the position of the source.

7.6.4.9. A statement of the restrictions, if any, that shall be placed on the weekly workload, degree of occupancy and the time that the useful beam may be directed at any shielding barrier.

7.6.4.10. If an installation is found not to comply with this standard, action required to ensure compliance shall be stated; if a resurvey will be required, it should be so stated.

7.7. **INSPECTIONS.** All radiation shields, interlocking switches and other safety devices shall be inspected periodically and appropriately serviced as scheduled by the radiation protection supervisor. The interval between inspections shall not exceed six months. (See 8.2)

7.7.1. Inspection shall be made by a competent person but not necessarily by a qualified expert.

7.7.2. Defective shielding barriers shall be promptly repaired and the inspection shall be repeated to determine whether the original degree of protection has been restored. If there is doubt about the adequacy of the repair, a qualified expert shall be consulted.

7.7.3. Inspection of protective devices is not a substitute for a radiation protection survey.

7.7.4. Records of inspection dates, findings, and corrective actions shall be kept on file.

8. Operating Procedures

8.1. **RESTRICTIONS ACCORDING TO CLASSIFICATION.**

8.1.1. **PROTECTIVE INSTALLATION.**

8.1.1.1. Since the inherent safety of the Protective Installation is dependent upon a higher degree of shielding, there are no restrictions on the mode of operation of the equipment.

8.1.1.2. If the enclosure is of such a size or is so arranged that the operator cannot readily determine whether the enclosure is unoccupied, the operator shall make a physical check of the enclosure before commencing or resuming operation.

8.1.2. **ENCLOSED INSTALLATION.**

8.1.2.1. Since the safe operation of an Enclosed Installation is based on the normal operating conditions specified in the applicable radiation protection survey report, the equipment shall be operated only within the indicated limits.

8.1.2.2. If the enclosure is of such a size or is so arranged that the operator cannot readily determine whether the enclosure is unoccupied, the operator shall make a physical check of the enclosure before commencing or resuming operation.

8.1.2.3. When the operating conditions have changed so that there is a probability that the exposure of any person may be increased, a radiation protection resurvey or evaluation shall be conducted. In case of doubt, a qualified expert should be consulted.

8.1.3. **UNATTENDED INSTALLATION.** No restrictions shall be imposed on the mode of operation of the equipment.

8.1.4. **OPEN INSTALLATION.**

8.1.4.1. The safe operation of an open installation relies upon operating personnel to survey areas and conduct the operation according to established procedures. Equipment shall be operated within limits established in paragraph 3.4.

8.1.4.2. A survey shall be made for each new operating condition and the area of operation should be periodically monitored. Surveillance of the area shall be maintained during operation.

8.1.4.3. When entering the operating area after irradiation, the operator shall use a suitable calibrated survey meter to verify that the source has been returned to its "off" position or that x-rays have been turned off.

8.2. **RADIATION PROTECTION RESPONSIBILITY.** The employer or his representative shall designate a competent person as the Radiation Protection Supervisor. This person shall be qualified by training or experience to carry out his duties as indicated below:

8.2.1. Insuring that all installations are operated within the limitations of the appropriate radiation protection survey reports.

8.2.2. The instruction of personnel in safe working practices and the nature of injuries resulting from overexposure to radiation.

8.2.3. Investigating any incident of abnormal exposure or suspected overexposure of personnel to determine the cause and take remedial action.

8.2.4. Assuring that interlock switches, warning signals and signs are functioning and located where required.

8.3. **RADIATION SAFETY INSTRUCTIONS.** Radiation safety instructions shall be posted and furnished to each radiation worker in writing.

8.4. **PERSONNEL MONITORING.**

8.4.1. Personnel monitoring shall be required for all workers involved in the use of radiation apparatus in Open and Enclosed Installations, and Protective Installations where personnel can enter the exposure area. Film badges or thermoluminescent dosimeters are acceptable for this purpose.

8.4.2. Personnel monitoring shall be performed in controlled areas for each occupationally exposed individual for whom there is a reasonable possibility of receiving a dose in any one calendar quarter exceeding one-fourth the applicable quarterly MPD (See table 1.)

8.4.3. For monitoring of personnel in Open Installations both film badges (or thermoluminescent dosimeters) and pocket dosimeters covering the range of 0 to 200 millirem should be used.

8.4.4. A qualified expert should be consulted on the establishment of personnel monitoring systems.

8.4.5. Records shall be kept concerning individual radiation exposures. These records shall include, as appropriate, results from individual film badges, pocket dosimeters or chambers, calculated results and the results of bioassay.

8.4.6. The guidance provided in ANSI N13.6–1966 (R 1972), Practice for Occupational Radiation Exposure Records System, should be considered for the purposes of this standard.

8.5. **RADIATION MEASUREMENT AND INSTRUMENT CALIBRATION.**

8.5.1. Sufficient and suitable radiation survey instruments shall be available to properly support the use of radiation sources. The instruments shall be capable of detecting and measuring the types and levels of radiation involved.

8.5.2. Each radiation survey instrument shall be calibrated at intervals not to exceed three months, and after each serviceing and repair. The calibration should be traceable to instruments or radiation sources calibrated at the National Bureau of Standards.

8.5.3. Pocket dosimeters or chambers shall be calibrated and checked for leakage at intervals not to exceed 6 months.

9. Revision of American National Standards Referred to in This Document

When the following American National Standards referred to in this document are superseded by a revision approved by the American National Standards Institute, Inc., the revision shall apply:

N2.1–1969, Radiation Symbol.

N2.3–1967, Immediate Evacuation Signal for Use in Industrial Installations where Radiation Exposure May Occur.

N13.6–1966 (R 1972), Occupational Radiation Exposure Records System, Practice for.

Appendix A. Occupancy and Use Factors

(This appendix is not a part of American National Standard N543, General Safety Standard for Installations Using Non-Medical X-Ray and Sealed Gamma Ray Sources, Energies up to 10 MeV.)

Table 2. *Occupancy factors* (*T*)

[For use as a guide in planning shielding where adequate occupancy data are not available.]

Full occupancy ($T=1$)
Control space, darkrooms, workrooms, shops, offices, and corridors large enough to be used as working areas, rest and lounge rooms routinely used by occupationally exposed personnel, living quarters, children's play areas, occupied space in adjoining buildings.
Partial occupancy ($T=1/4$)
Corridors too narrow for desks, utility rooms, rest and lounge rooms not used routinely by occupationally exposed personnel, elevators using operators, unattended parking lots.
Occasional occupancy ($T=1/16$)
Closets too small for future occupancy, toilets not used routinely by occupationally exposed personnel, stairways, automatic elevators, outside areas used only for pedestrians or vehicular traffic.

Table 3. *Use factors* (*U*)

[For use as a guide in planning shielding when complete data are not available.]

Installation use	Protective all uses	Enclosed	
		Collimated sources	Open sources
Floor	1	1	1
Walls	1	1/4	1
Ceiling	1	1/16	1

Appendix B. Determination of Gamma-Ray Shielding Barrier Thicknesses

(This appendix is not a part of American National Standard N543, General Safety Standard for Installations Using Non-Medical X-Ray and Sealed Gamma-Ray Sources, Energies up to 10 MeV.)

The thickness of shielding barrier necessary to reduce the gamma rays from a sealed gamma source to the maximum permissible level depends upon the energy of the radiation, source strength, design of the source housing, beam diameter, scattered radiation from irradiated objects, the use factor (fraction of the time during which the radiation is incident on the barrier), distance from the source to occupied areas, degree and nature of occupancy, type of installation, and the material of which the barrier is constructed.

Table 4 gives data on radioactive gamma-ray sources of interest for industrial purposes, including the energy of the gamma rays emitted. Tables 5 through 8 give shielding requirements for several commonly used types of source. Occasionally, conditions are not covered by the tables and it will then be necessary to resort to computation of the shielding requirements by using the transmission curves in various materials, figures 4 through 17.

TABLE 4. *Gamma-ray sources*

Radioisotope	Atomic number	Half-life	Gamma-ray energy	Specific gamma-ray constant
	Z		MeV	*R/curie*[a] *h at 1 m*
Cesium 137	55	27y	0. 662	0. 32
Chromium 51	24	28d	0. 323	[c] 0. 018
Cobalt 60	27	5.2y	1. 17, 1. 33	1. 3
Gold 198	79	2.7d	0. 412	0. 23
Iridium 192	77	74d	0. 136, 1. 065	[c] 0. 5
Radium 226	88	1622y	0. 047 to 2. 4	[b] 0. 825
Tantalum 182	73	115d	0. 066 to 1. 2	[c] 0. 6

[a] These values assume that gamma-ray absorption in the source is negligible. Value in R/curie h at 1 m can be converted to R/millicurie h at 1 cm by multiplying by 10.

[b] This value assumes that the source is sealed within a 0.50-mm thick platinum capsule.

[c] These values are less certain and in some cases are estimates.

The computation of the gamma shielding requirements may be simplified by considering separately: (a) the useful beam, (b) the radiation transmitted through the source housing (leakage radiation), and (c) the scattered radiation.[2]

USEFUL BEAM. The primary-shielding-barrier thickness may be obtained from figures 4, 5 and 6 if the permissible transmission of radiation is known.

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[2] Equations (1) to (3) and the pertinent attenuation curves give the thickness of barrier when the radiation is incident normal to the surface. When the radiation is incident obliquely to the surface at an angle θ, the thickness of the barrier may not be equal to the thickness given by the equations and curves multiplied by the cosine for very oblique angles (7).

If more than one source will produce appreciable radiation in the occupied area, then all such sources must be considered in the barrier design.

The permissible transmission, B, may be calculated from

$$B=\frac{Pd^2}{WUT(3.28)^2}=\frac{0.1Pd^2}{WUT} \tag{1}$$

where

P is the permissible average weekly exposure (in roentgens) for design purposes, having a value of 0.1R for controlled areas and 0.01 R for the environs,

d is the distance from source to the position in question (in feet),

W is the weekly exposure in the useful beam at 1 m from the source (obtained by multiplying the roentgens per minute at 1 m by the weekly irradiation time in minutes, averaged over a year),

T is the occupancy factor, the fraction of the yearly irradiation time during which a person is exposed (see table 2, appendix A),

U is the use factor, the fraction of the workload during which the useful beam is pointed in the direction under consideration, and

3.28 is the conversion from meters to feet.

LEAKAGE RADIATION. Equation (1) may be used to compute the barrier requirements for this radiation, where W is the leakage radiation in roentgens per week measured at 1 m from the source, and U is equal to 1.

SCATTERED RADIATION. Radiation scattered from an irradiated object has a lower rate and is softer (of lower energy) than the incident beam. Both the energy and dose rate of the scattered beam vary with the angle of scattering and atomic number of the scatterer. Figures 7 and 8, the variation of $B_s\times(D_s/D_u)$ with barrier thickness, where B_s is the fractional transmission of the barrier, D_s is the unattenuated dose in the scattered beam at 1 m from the scatterer, and D_u is the dose incident on the scatterer. If the scatterer is at 1 m from the source and the field diameter is that given in the curves of figures 7 and 8

$$B_s\times\frac{D_s}{D_u}=\frac{0.1Pd^2}{WT}. \tag{2}$$

If the scatterer is at 50 cm from the source and the field diameter is that given in the curves of figures 7 and 8

$$B_s\times\frac{D_s}{D_u}=\frac{0.025Pd^2}{WT} \tag{3}$$

for the same field size.

SECONDARY SHIELDING BARRIERS. The rules given above for scattered radiation and for leakage radiation may be used to compute the secondary-shielding-barrier thickness for each of the two separate effects. If the barrier thicknesses so computed separately are nearly equal (that is, differ by less than 3 HVL), then 1 HVL should be added to the larger single-barrier thickness to obtain the required total.[3] But if one of the thicknesses is more than 3 HVL greater than the other, the thicker one alone is adequate.[4]

SHIELDING. If the shielding is adequate for the useful radiation, that is, if it is a primary shielding barrier, it is more than adequate for leakage and scattered radiation. It should be determined, however, that radiation scattered around the primary shielding barrier does not cause a radiation hazard.

For reasons of economy, barriers usually should be placed as near to the source as possible. The barrier thickness is not reduced by this procedure but the area and therefore the volume are reduced; the barrier weight is approximately proportional to the square of the distance between the source and the barrier.

Concrete, marble, and similar materials generally provide the most economical barrier but lead may be required where the space is limited or where it is desirable to reduce the weight.

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[3] Each of the two effects thus produce a permissible dose. Together they produce twice the permissible dose. This radiation can be reduced to the permissible level by the addition of 1 HVL.

[4] The larger thickness will permit transmission of the permissible level from one effect, plus not more than one-eighth (3 HVL) of the permissible level from the other effect. This one-eighth excess is negligible in view of other conservative approximations that are involved.

TABLE 5A. *Cobalt 60 shielding requirements for controlled areas* [a]

WUT [b]	Curies [c] approx.		Distance from source to occupied areas (ft)										
80,000	2000		5	7	10	14	20	28	40				
40,000	1000			5	7	10	14	20	28	40			
20,000	500				5	7	10	14	20	28	40		
10,000	250					5	7	10	14	20	28	40	
5,000							5	7	10	14	20	28	40
2,500								5	7	10	14	20	28
1,250									5	7	10	14	20
625										5	7	10	14
310											5	7	10
Type of barrier	Approx.		Thickness of lead (cm)										
	HVL (cm)	TVL (cm)											
Primary	1.20	4.0	22.5	21.3	20.1	18.9	17.7	16.5	15.3	14.1	12.9	11.7	10.5
Secondary:													
Leakage [d] 0.1%	1.20	4.0	10.5	9.3	8.2	7.1	6.0	4.7	3.4	2.0	0.6	0	0
0.05%	1.20	4.0	9.3	8.2	7.1	6.0	4.7	3.4	2.0	0.6	0	0	0
Scatter [e] 30°	1.02	3.40	12.15	11.10	10.10	9.05	8.00	7.00	6.00	4.95	3.95	2.95	1.95
45°	0.87	2.90	9.65	8.75	7.90	7.00	6.15	5.25	4.35	3.50	2.65	1.75	0.90
60°	0.75	2.50	7.65	6.90	6.15	5.40	4.65	3.90	3.15	2.4	1.65	0.9	0.25
90°	0.43	1.45	3.60	3.15	2.70	2.30	1.85	1.40	1.00	0.60	0.25	0.03	0
120°	0.20	0.65	1.45	1.25	1.05	0.85	0.65	0.45	0.30	0.15	0.05	0	0
150°	0.14	0.45	0.90	0.75	0.65	0.50	0.40	0.25	0.15	0.08	0.02	0	0

[a] For a weekly design level of 100 mR; add one tenth-value layer (TVL) for regions in the environs to reduce radiation to 10 mR/week.

[b] W=workload in R/week at 1 m, U=use factor, T=occupancy factor.

[c] Assumes use factor (U) and occupancy factor (T) are equal to one.

[d] Refers to leakage radiation of source housing; may be ignored if less than 2.5 mR/h at 1 m in "on" position.

[e] For large field (20 cm diam) and a source-phantom distance of 40 to 60 cm. This includes scattering from the collimator and from the phantom. (From Braestrup and Wyckoff [1].)

TABLE 5B. *Cobalt 60 shielding requirements for controlled areas*[a]

WUT[b]	Curies[c] approx.	Distance from source to occupied areas (ft)										
80,000	2000	5	7	10	14	20	28	40				
40,000	1000		5	7	10	14	20	28	40			
20,000	500			5	7	10	14	20	28	40		
10,000	250				5	7	10	14	20	28	40	
5,000						5	7	10	14	20	28	40
2,500							5	7	10	14	20	28
1,250								5	7	10	14	20
625									5	7	10	14
310										5	7	10

Type of barrier	Approx.		Thickness of concrete (density 147 lb/cu ft) (in.)										
	HVL (in)	TVL (in)											
Primary	2.6	8.6	47.5	45.1	42.7	40.3	37.8	35.4	32.9	30.5	28.0	25.6	23.1
Secondary:													
Leakage[d] 0.1%	2.6	8.6	23.1	20.7	18.3	15.6	12.9	10.2	7.3	4.4	1.4	0	0
0.05%	2.6	8.6	20.7	18.3	15.6	12.9	10.2	7.3	4.4	1.4	0	0	0
Scatter[e] 30°	2.5	8.2	30.6	28.1	25.7	23.2	20.6	18.2	15.8	13.3	10.9	8.4	5.9
45°	2.4	8.0	27.0	24.6	22.2	19.8	17.4	15.0	12.6	10.2	7.8	5.4	3.0
60°	2.3	7.6	24.0	21.7	19.4	17.1	14.8	12.3	10.0	7.7	5.4	3.0	0.5
90°	1.8	6.2	16.9	15.0	13.2	11.4	9.6	7.8	6.0	4.1	2.1	0.1	0
120°	1.7	5.8	15.0	13.3	11.6	9.9	8.2	6.5	4.7	3.0	1.2	0	0
150°	1.5	5.0	12.5	11.0	9.6	8.1	6.6	5.1	3.7	2.2	0.8	0	0

[a] For a weekly design level of 100 mR; add one tenth-value layer (TVL) for regions in the environs to reduce radiation to 10 mR/week.

[b] W=workload in R/week at 1 m, U=use factor, T=occupancy factor.

[c] Assumes use factor (U) and occupancy factor (T) are equal to one.

[d] Refers to leakage radiation of source housing; may be ignored if less than 2.5 mR/h at 1 m in "on" position.

[e] For large field (20 cm diam) and a source-phantom distance of 40 to 60 cm. This includes scattering from the collimator and from the phantom. (From Braestrup and Wyckoff [1].)

TABLE 6A. *Cesium-137 Shielding requirements for controlled areas* [a]

WUT[b] in R/week at 1 meter			Distance in Feet from Source to Occupied Area										
24,000			5	7	10	14	20	28	40				
12,000				5	7	10	14	20	28	40			
6,000					5	7	10	14	20	28	40		
3,000						5	7	10	14	20	28	40	
1,500							5	7	10	14	20	28	40
750								5	7	10	14	20	28
375									5	7	10	14	20
Type of Protective Barrier	Approx. *HVL* cm of Lead	Approx. *TVL* cm of Lead	Lead Thickness in Centimeters										
Primary	0.65	2.1	10.5	9.9	9.3	8.6	8.0	7.4	6.7	6.1	5.5	4.8	4.1
Secondary													
Leakage [c]													
0.1%	0.65	2.1	4.2	3.5	2.9	2.3	1.6	1.0	0.4	0	0	0	0
0.05%	0.65	2.1	3.5	2.9	2.3	1.6	1.0	0.4	0	0	0	0	0
Scatter [d]													
35°	0.45	1.5	5.3	4.9	4.4	3.9	3.5	3.0	2.6	2.2	1.7	1.3	0.8
45°	0.41	1.4	4.7	4.3	3.9	3.5	3.1	2.7	2.3	1.9	1.5	1.1	0.7
60°	0.38	1.3	4.1	3.7	3.3	2.9	2.5	2.1	1.7	1.4	1.0	0.7	0.4
90°	0.22	0.7	2.0	1.8	1.6	1.3	1.1	0.9	0.7	0.5	0.4	0.2	0.1
120°	0.13	0.4	1.0	0.9	0.8	0.7	0.6	0.5	0.3	0.2	0.2	0.1	0

[a] For a weekly design level of 100 mR; add one tenth-value layer (*TVL*) for noncontrolled areas, to reduce to 10 mR/week.

[b] *W*—workload in R/week at 1 m, *U*—use factor, *T*—occupancy factor.

[c] Refers to leakage radiation of source housing when source in "ON" condition; may be ignored if less than 2.5 mR/h at 1 m.

[d] For large field (20 cm diam) and a source-scatterer distance of 50 cm. This includes only scattering from an obliquely positioned flat scatterer.

[From NCRP Report No. 34.]

TABLE 6B. *Cesium-137 shielding requirements for controlled areas* [a]

WUT[b] in R/week at 1 meter			Distance in Feet from Source to Occupied Area										
24,000			5	7	10	14	20	28	40				
12,000				5	7	10	14	20	28	40			
6,000					5	7	10	14	20	28	40		
3,000						5	7	10	14	20	28	40	
1,500							5	7	10	14	20	28	40
750								5	7	10	14	20	28
375									5	7	10	14	20
Type of Protective Barrier	Approx. *HVL* Inches of Concrete	Approx. *TVL* Inches of Concrete	Concrete Thickness in Inches[c]										
Primary	1.9	6.2	34.1	32.2	30.2	28.3	26.3	24.4	22.4	20.6	18.7	16.8	14.8
Secondary													
Leakage[d]													
0.1%	1.9	6.2	15.5	13.6	11.5	9.6	7.7	5.8	3.9	2.0	0	0	0
0.05%	1.9	6.2	13.6	11.5	9.6	7.7	5.8	3.9	2.0	0	0	0	0
Scatter[e]													
35°	1.8	6.1	21.5	19.7	17.9	16.1	14.3	12.5	10.7	8.9	7.1	5.3	3.5
45°	1.6	5.4	18.0	16.4	14.8	13.2	11.6	10.0	8.4	6.8	5.2	3.6	2.0
60°	1.5	4.9	15.8	14.3	12.8	11.3	9.8	8.3	6.8	5.3	3.8	2.3	0.8
90°	1.4	4.7	14.5	13.1	11.7	10.3	8.9	7.5	6.1	4.7	3.3	1.9	0.5
120°	1.3	4.4	13.1	11.8	10.5	9.2	7.9	6.6	5.3	4.0	2.7	1.4	0

[a] For a weekly design level of 100 mR; add one tenth-value layer (*TVL*) for regions in the environs to reduce to 10 mR/week.

[b] *W*—workload in R/week at 1 m, *U*—use factor, *T*—occupancy factor.

[c] Thickness based on concrete density of 2.35 g/cm^3 (147 lb/ft^3).

[d] Refers to leakage radiation of source housing when source in "ON" condition; may be ignored if less than 2.5 mR/h at 1 m.

[e] For large field (20 cm diam) and a source-scatterer distance of 50 cm. This includes only scattering from an obliquely positioned flat scatterer.

[From NCRP Report No. 34.]

TABLE 7. *Relation between distance and millicurie-hours for an exposure of 0.1 R from an unshielded source*

Millicurie-hours	Distance to source				
	Radium	Cobalt 60	Cesium 137	Iridium 192	Gold 198
	ft	*ft*	*ft*	*ft*	*ft*
10	0.9	1.2	0.6	0.7	0.5
30	1.6	2.1	1.0	1.3	0.9
100	3.0	3.8	1.9	2.3	1.6
300	5.1	6.5	3.2	4.0	2.7
1,000	9.4	11.9	5.8	7.4	5.0
3,000	16.3	20.5	10.1	12.7	9.0
10,000	30.1	37.6	18.5	23.2	15.8

TABLE 8. *Protection requirements (in centimeters of lead) for various gamma-ray sources*

Millicurie-hours	Radium TVL[a]=5.5 cm lead			Cobalt 60 TVL[a]=4.1 cm lead			Cesium 137 TVL[a]=2.2 cm lead		
	Thickness of lead required to reduce radiation to 100 mR [b] at a distance of—								
	1 ft	3.2 ft	6.5 ft	1 ft	3.2 ft	6.5 ft	1 ft	3.2 ft	6.5 ft
100	4.0	0	0	5.0	0.7	0	1.1	0	0
300	6.2	1.5	0	7.0	2.8	0	2.1	0	0
1,000	8.9	3.6	1.1	9.1	4.9	2.5	3.3	1.1	0
3.000	11.3	5.8	3.1	11.0	6.8	4.4	4.3	2.1	0.8
10,000	14.1	8.5	5.5	13.1	8.9	6.5	5.4	3.2	1.9
30,000	16.7	11.0	7.8	15.0	10.8	8.4	6.4	4.2	2.9
100,000	19.5	13.7	10.5	17.2	12.9	10.5	7.5	5.3	4.0

Millicurie-hours	Iridium 192 TVL[a]=2.0 cm lead			Gold 198 TVL[a]=1.1 cm lead		
	Thickness of lead required to reduce radiation to 100 mR [b] at a distance of—					
	1 ft	3.2 ft	6.5 ft	1 ft	3.2 ft	6.5 ft
100	0.8	0	0	0.4	0	0
300	1.4	0.1	0	0.9	0	0
1,000	2.2	0.7	0.1	1.5	0.3	0
3,000	3.1	1.4	0.6	2.1	0.9	0.2
10,000	4.0	2.1	1.2	3.0	1.4	0.8
30,000	5.0	3.0	2.0	3.9	2.0	1.3
100,000	6.2	4.0	2.8	5.3	2.9	1.9

[a] Approximate value obtained with large attenuation.
[b] Add one tenth-value layer (TVL) to reduce radiation to 10 mR.

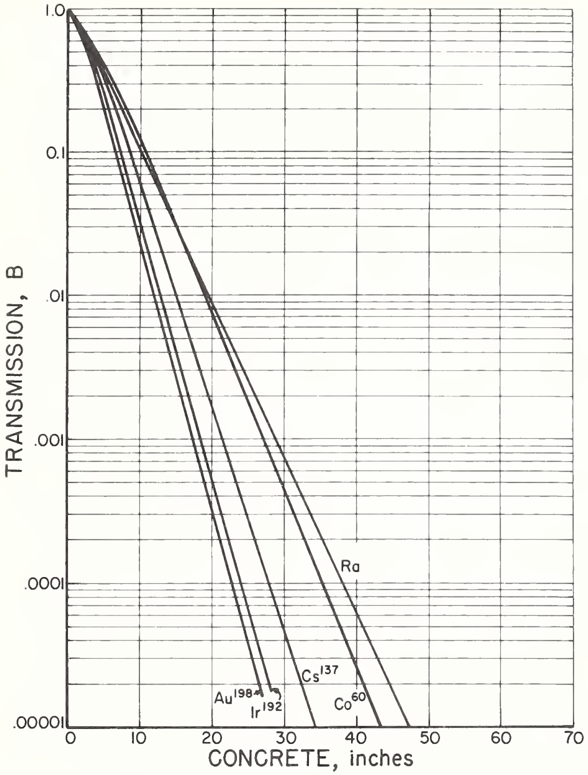

FIGURE 4. *Transmission through concrete (density 147 lb/ft^3) of gamma rays from radium [14]; cobalt 60, cesium 137, gold 198 [7]; iridium 192 [15].*

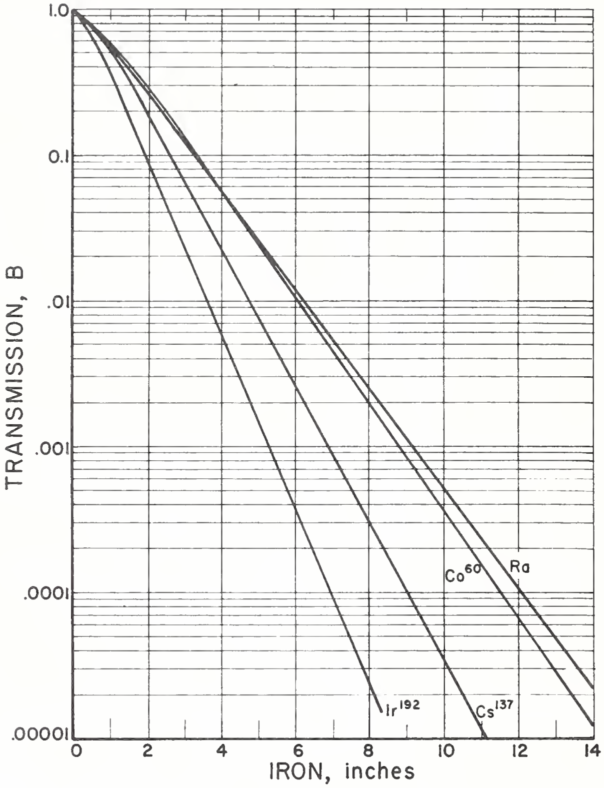

FIGURE 5. *Transmission through iron of gamma rays from radium [14]; cobalt 60, cesium 137 [7]; iridium 192 [15].*

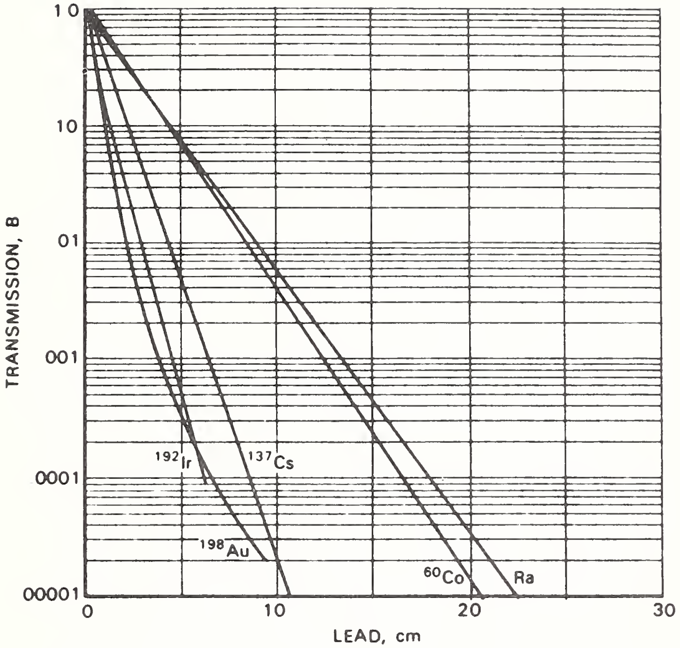

FIGURE 6. *Transmission through lead of gamma rays from selected radionuclides.*

Radium (Wyckoff and Kennedy [14]), cobalt-60, cesium-137, gold-198 (Kirn et al. [7]), iridium-192 (Ritz [15]).

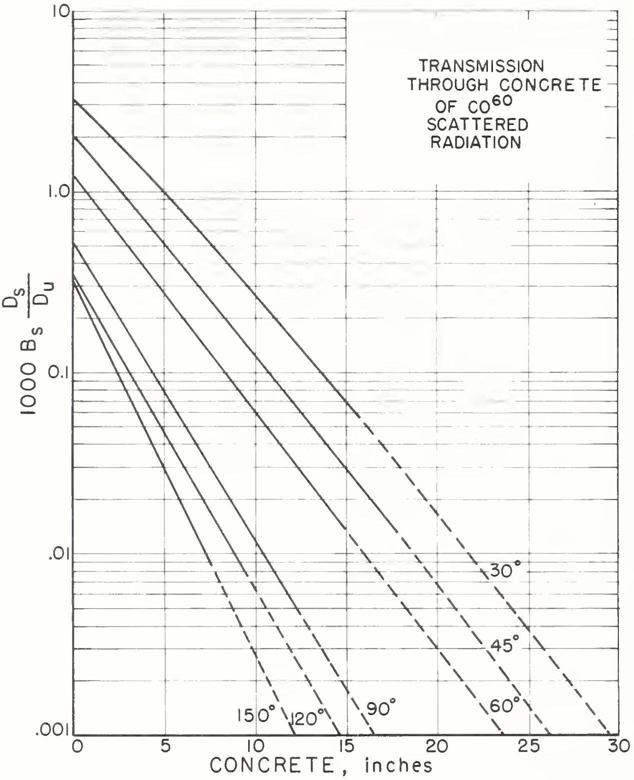

FIGURE 7a. *Transmission through concrete (density 147 lb/ft*^{3}*) of cobalt 60 scattered radiation from cylindrical Masonite phantom, 20-cm diam field at 1 m from source [10].*

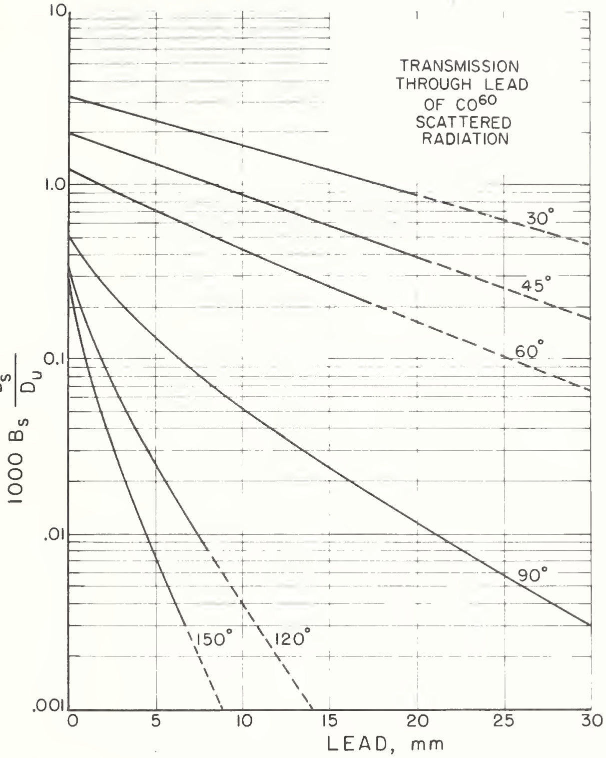

FIGURE 7b. *Transmission through lead of cobalt 60 scattered radiation from cylindrical Masonite phantom, 20-cm diam field at 1 m from source [10].*

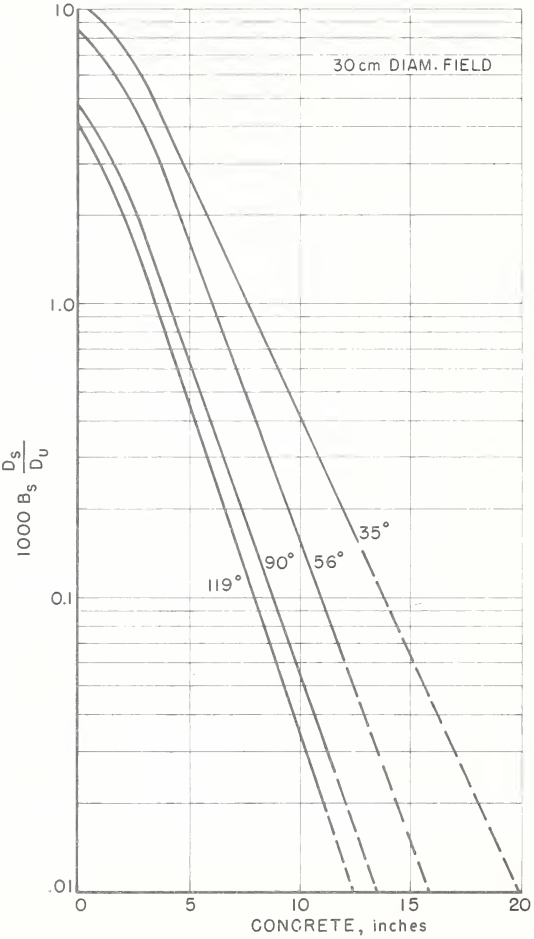

FIGURE 8a. *Transmission through concrete (density 147 lb/ft^3) of cesium 137 radiation scattered at the indicated angles from an oblique concrete barrier [4].*

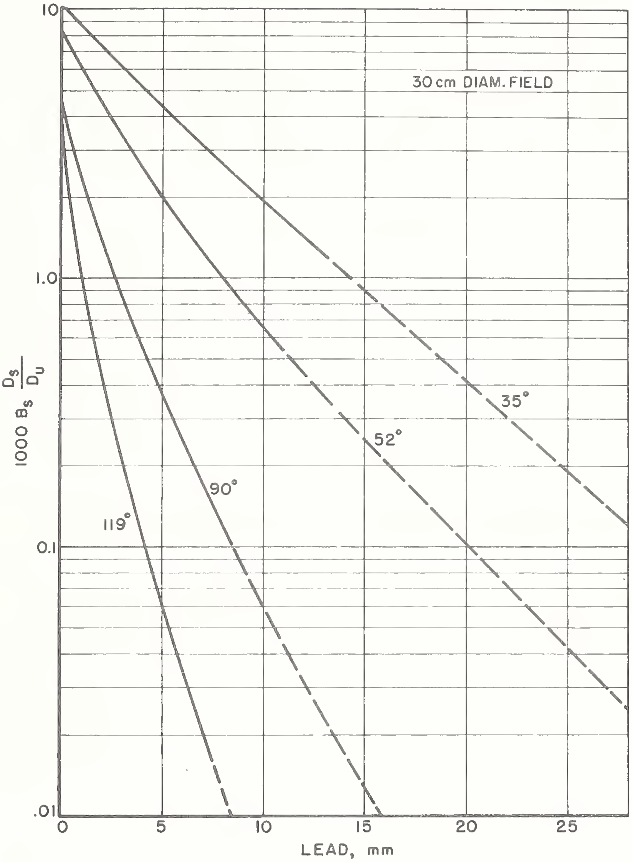

FIGURE 8b. *Transmission through lead of cesium 137 radiation scattered at the indicated angles from an oblique concrete barrier [4].*

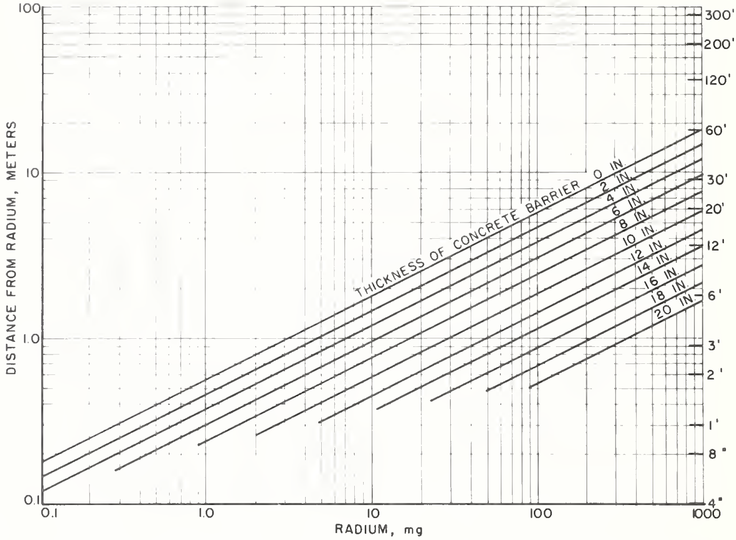

FIGURE 9. *Relation between amount of radium, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 h.*

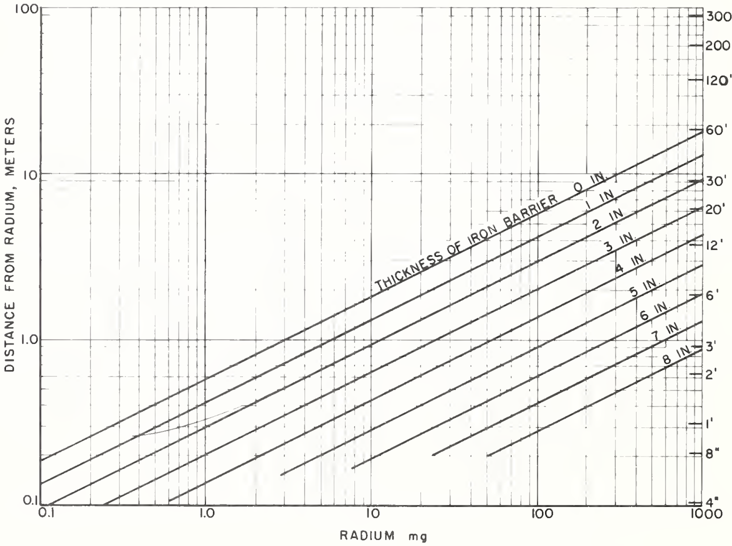

FIGURE 10. *Relation between amount of radium, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 h.*

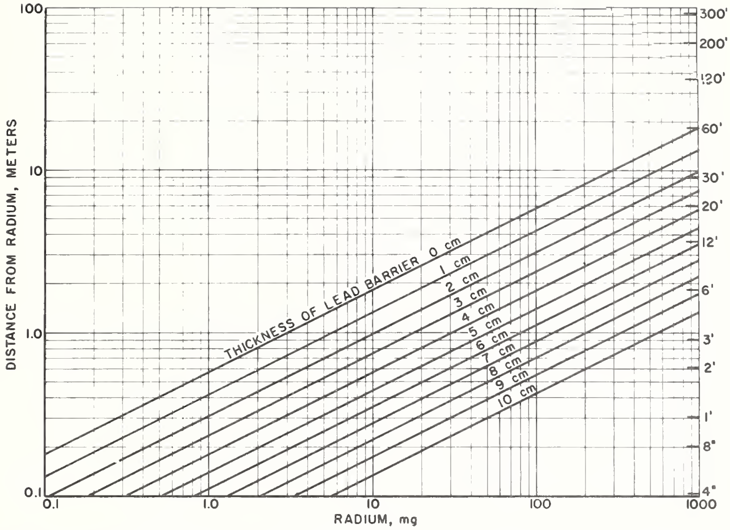

FIGURE 11. *Relation between amount of radium, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 h.*

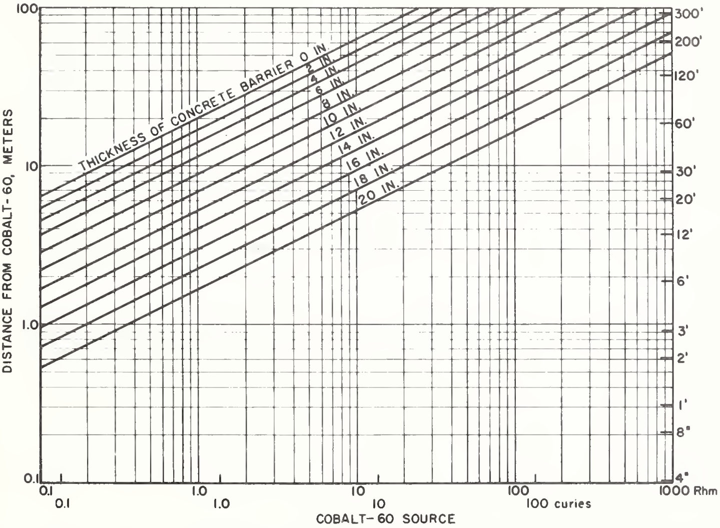

FIGURE 12. *Relation between amount of cobalt 60 or Rhm, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 h.*

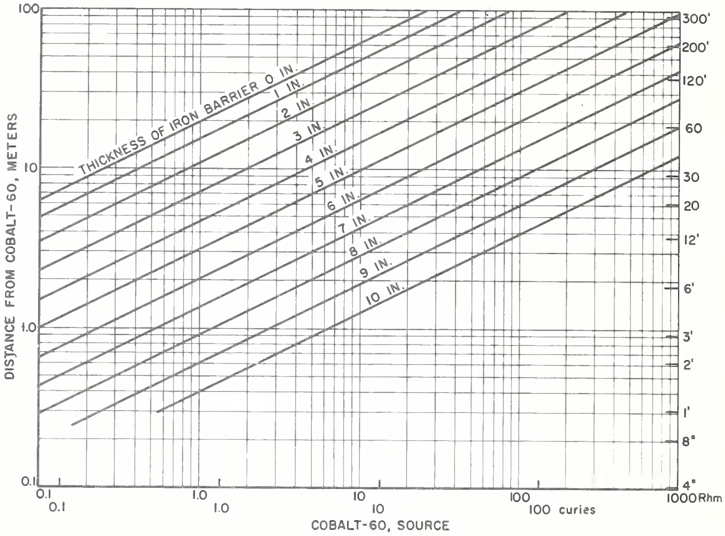

FIGURE 13. *Relation between amount of cobalt 60 or Rhm, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 h.*

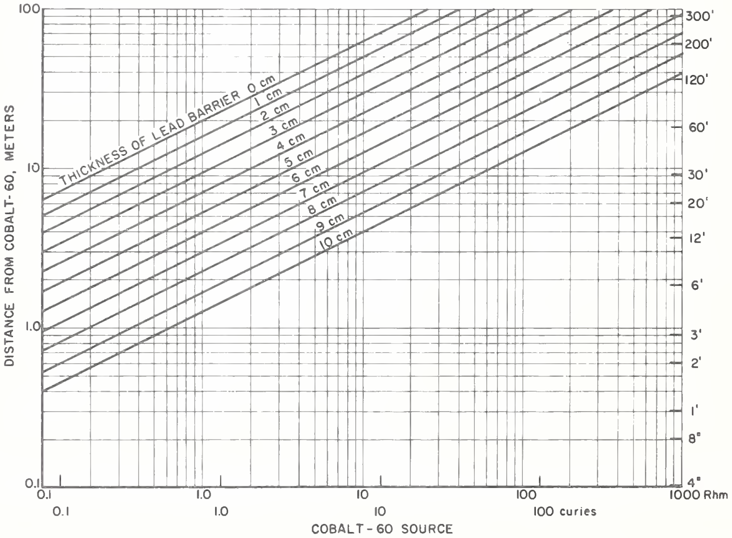

FIGURE 14. *Relation between amount of cobalt 60 or Rhm, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 h.*

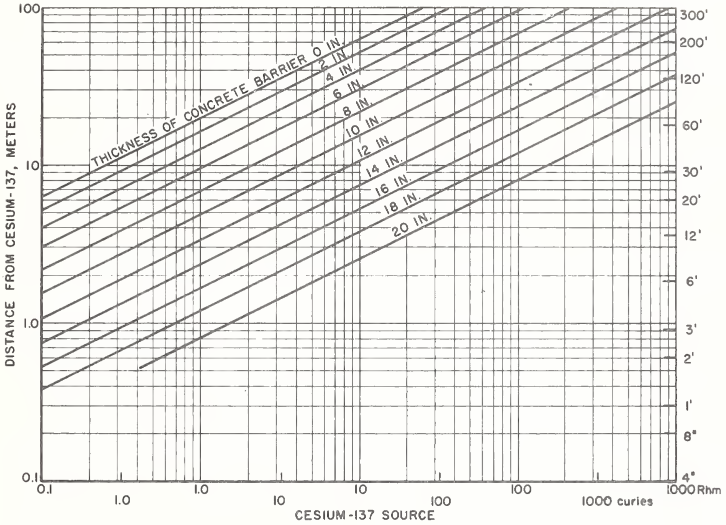

FIGURE 15. *Relation between amount of cesium 137 or Rhm, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 h.*

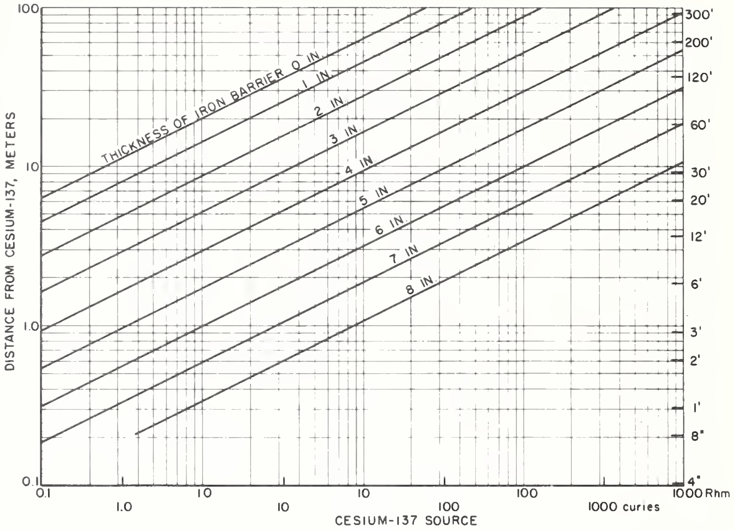

FIGURE 16. *Relation between amount of cesium 137 or Rhm, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 h.*

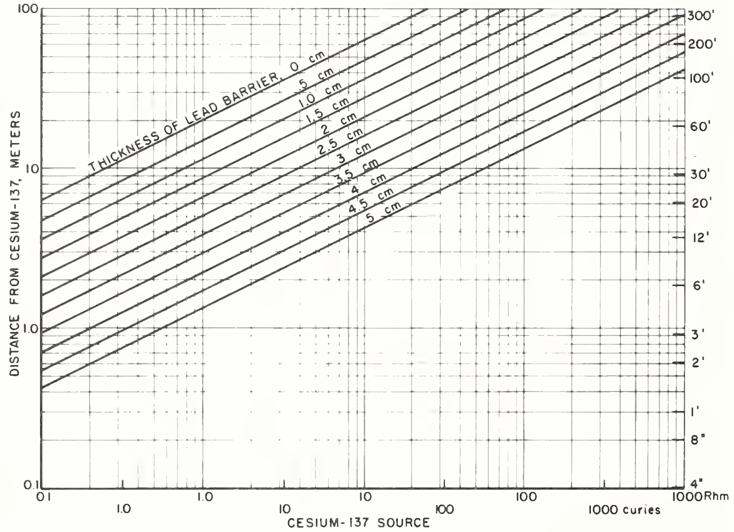

FIGURE 17. *Relation between amount of cesium 137 or Rhm, distance, and shielding for controlled areas to reduce exposure to 0.1 R per 40 h.*

Appendix C. Tables of General X-Ray Information

(This appendix is not a part of American National Standard N543, General Safety Standard for Installations Using Non-Medical X-Ray and Sealed Gamma Ray Sources, Energies up to 10 MeV.)

Some of the tables included in this appendix and in appendix D (tables 12, 15A, and 15B) refer to a protective tube housing, which is defined as a tube housing so constructed that the leakage radiation at a distance of one meter from the target does not exceed one roentgen in one hour when the tube is operated at its maximum rating. The leakage radiation should be averaged over an area of 100 cm^2.

TABLE 9. *Distance protection (in feet) against useful beam in controlled areas*

[For design purposes only, the maximum permissible exposure is taken to be 100 mR/wk.]

Kilovoltage	50	70	100	250	1,000	2,000
X-ray output (K_0) (R/ma-min at 1 m)	0.05	0.1	0.4	2	20	280
WUT[a]	Distance in feet					
2	3	5	9	20	60	200
4	5	7	13	28	76	270
7	6	9	17	37	105	335
8	7	10	19	40	115	350
12	8	12	23	47	130	415
15	9	13	25	52	145	450
30	12	17	35	69	190	550
50	15	22	44	85	230	650
60	16	24	47	92	240	700
125	22	33	62	120	320	850
150	24	35	66	130	335	880
200	27	38	75	140	375	950
250	30	42	80	155	400	1, 000
500	40	55	100	200	500	1, 150
600	42	58	107	210	530	1, 200
800	47	65	120	235	570	1, 275
1,000	50	70	130	250	600	1, 350
2,000	62	85	165	310	720	1, 500
2,500	69	90	175	330	760	1, 575
4,000	75	102	200	370	850	1, 700
10,000	95	130	250	480	1, 030	1, 950
40,000	125	180	350	640	1, 300	2, 350

[a] *W*=workload in milliampere-minutes per week.
U=use factor.
T=occupancy factor.

TABLE 10. *Distance protection (in feet) against useful beam in areas outside of controlled areas (environs)*

[For design purposes only, the maximum permissible exposure is taken to be 10 mR/wk.]

Kilovoltage	50	70	100	250	1,000	2,000
X-ray output (K_0) (R/ma-min at 1 m)	0.05	0.1	0.4	2	20	280
WUT[a]	Distance in feet					
2	11	15	30	50	160	480
4	15	20	38	77	220	590
7	18	25	50	95	255	690
8	20	27	52	100	270	720
12	23	31	60	116	310	800
15	25	35	65	127	340	850
30	32	45	85	165	430	1,000
50	38	55	102	195	510	1,150
60	40	59	110	210	530	1,200
125	53	78	140	265	670	1,400
150	56	84	150	280	700	1,450
200	62	95	165	310	750	1,550
250	65	102	175	330	800	1,600
500	85	130	220	400	940	1,800
600	90	145	232	420	990	1,850
800	100	150	250	460	1,050	1,920
1,000	110	160	270	490	1,100	2,000
2,000	135	200	330	570	1,250	2,150
2,500	145	210	345	600	1,300	2,200
4,000	165	240	375	650	1,400	2,300
10,000	210	300	460	750	1,550	2,550
40,000	280	390	580	900	1,750	2,850

[a] *W*=workload in milliampere-minutes per week.
U=use factor.
T=occupancy factor.

TABLE 11. *Half-value and tenth-value layers*

Approximate values obtained at *high attenuation* for the indicated peak voltage values under broad-beam conditions; with *low attenuation* these values will be significantly less.

Peak Voltage (kV)	Attenuating Material					
	Lead (mm)		Concrete (in.)		Steel (in.)	
	HVL	*TVL*	*HVL*	*TVL*	*HVL*	*TVL*
50	0.05	0.16	0.17	0.6		
70	0.15	0.5	0.33	1.1		
100	0.24	0.8	0.6	2.0		
125	0.27	0.9	0.8	2.6		
150	0.29	0.95	0.88	2.9		
200	0.48	1.6	1.0	3.3		
250	0.9	3.0	1.1	3.7		
300	1.4	4.6	1.23	4.1		
400	2.2	7.3	1.3	4.3		
500	3.6	11.9	1.4	4.6		
1,000	7.9	26	1.75	5.8		
2,000	12.7	42	2.5	8.3		
3,000	14.7	48.5	2.9	9.5		
4,000	16.5	54.8	3.6	12.0	1.08	3.6
6,000	17.0	56.6	4.1	13.7	1.2	4.0
10,000	16.5	55.0	4.6	15.3		
Cesium-137	6.5	21.6	1.9	6.2	0.64	2.1
Cobalt-60	12	40	2.45	8.1	0.82	2.7
Radium	16.6	55	2.7	9.2	0.88	2.9

[From NCRP Report No. 34.]

TABLE 12. *Secondary barrier requirements for leakage radiation from protective tube housings for controlled areas*

[Add 3.3 hvl for environs]

Distance from target in feet	Operating time in hours per week					
	2	5	10	15	25	40
	Number of half-value layers					
3	4.6	5.9	6.9	7.5	8.2	8.9
4	3.8	5.1	6.1	6.7	7.4	8.1
5	3.2	4.5	5.5	6.1	6.8	7.4
6	2.6	3.9	4.9	5.5	6.3	7.0
7	2.2	3.5	4.5	5.1	5.8	6.5
8	1.8	3.1	4.1	4.7	5.4	6.1
9	1.5	2.8	3.7	4.3	5.1	5.8
10	1.2	2.5	3.5	4.0	4.8	5.5
12	0.6	1.9	2.9	3.5	4.3	4.9
15	0.2	1.3	2.3	2.9	3.6	4.3
20	------	0.5	1.5	2.0	2.8	3.5
30	------	------	0.3	0.9	1.6	2.3

TABLE 13. *Densities of commercial building materials*

Material	Average density[a]	
	g/cm³	lb/ft³
Aluminum	2.7	169
Bricks:		
Fire clay	2.05	128
Kaolin	2.1	131
Silica	1.78	111
Clay	2.2	137
Cements:		
Colemanite borated	1.95	122
Plain (1 Portland cement: 3 sand mixture)	2.07	129
Concretes:		
Barytes[b]	3.5	218
Barytes-boron frits[b]	3.25	203
Barytes-limonite[b]	3.25	203
Barytes-lumnite-colemanite[b]	3.1	194
Iron-Portland[b]	6.0	375
MO (ORNL mixture)	5.8	362
Portland (1 cement: 2 sand: 4 gravel)	2.2	137
Glass:		
Borosilicate	2.23	139
Lead (hi-D)	6.4	399
Plate (avg.)	2.4	150
Iron	7.86	491
Lead	11.34	708
Lucite (polymethyl methacrylate)	1.19	74
Rocks:		
Granite	2.45	153
Limestone	2.91	182
Sandstone	2.40	150
Sand	2.2	137
Sand plaster	1.54	96
Type 347 stainless steel	7.8	487
Steel (1% carbon)	7.83	489
Uranium	18.7	1,167
Uranium hydride	11.5	718
Water	1.0	62

[a] Compiled from data in Ref. [26].

[b] Concrete mixtures for shielding reported by R. B. Gallaher and A S. Kitzes, Summary Report on Portland Cement Concretes for Shielding, USAEC Report ORNL–1414, Oak Ridge National Laboratory, March 2, 1953.

TABLE 14. *Commercial lead sheets*

Thickness		Weight in pounds for a 1 square foot section	
Inches	Millimeter equivalent	Nominal weight	Actual weight
$^{1}/_{64}$	0.40	1	0.92
$^{3}/_{128}$	0.60	$1^{1}/_{2}$	1.38
$^{1}/_{32}$	0.79	2	1.85
$^{5}/_{128}$	1.00	$2^{1}/_{2}$	2.31
$^{3}/_{64}$	1.19	3	2.76
$^{7}/_{128}$	1.39	$3^{1}/_{2}$	3.22
–	1.50	–	3.48
$^{1}/_{16}$	1.58	4	3.69
$^{5}/_{64}$	1.98	5	4.60
$^{3}/_{32}$	2.38	6	5.53
–	2.5	–	5.80
–	3.0	–	6.98
$^{1}/_{8}$	3.17	8	7.38
$^{5}/_{32}$	3.97	10	9.22
$^{3}/_{16}$	4.76	12	11.06
$^{7}/_{32}$	5.55	14	12.9
$^{1}/_{4}$	6.35	16	14.75
$^{1}/_{3}$	8.47	20	19.66
$^{2}/_{5}$	10.76	24	23.60
$^{1}/_{2}$	12.70	30	29.50
$^{2}/_{3}$	16.93	40	39.33
1	25.40	60	59.00

Notes:

1. The density of commercially rolled lead is 11.36 g/cm^3.
2. The commercial tolerances are ±0.005 inches for lead up to $^{7}/_{128}$ and $\pm ^{1}/_{32}$ for heavier sheets.
3. It should be noted that lead sheet less than $^{1}/_{32}$ inch thick is frequently more expensive than heavier sheet in cost of material and cost of installation.

*Permission: Lead Industries Association, Inc., 292 Madison Ave., New York.

[From NCRP Report No. 34.]

Appendix D. X-Ray Shielding Tables for Controlled Areas and Environs

(This appendix is not a part of American National Standard N543, General Safety Standard for Installations Using Non-Medical X-Ray and Sealed Gamma Ray Sources, Energies up to 10 MeV.)

TABLE 15A. *Industrial x-ray shielding requirements for controlled areas* [a] [1]

[b] *WUT*				Distance from tube to occupied area *ft*										
40,000				5	7	10	14	20	28	40				
20,000					5	7	10	14	20	28	40			
10,000						5	7	10	14	20	28	40		
5,000							5	7	10	14	20	28	40	
2,500								5	7	10	14	20	28	40
1,250									5	7	10	14	20	28
625										5	7	10	14	20
310											5	7	10	14
155												5	7	10
Potential	Approximate [c] HVL	Approximate [c] TVL	Type of barrier [d]	Thickness of lead *mm*										
kv	*mm*	*mm*												
100	0.2	0.7	Prim.	3.2	2.9	2.7	2.4	2.2	1.9	1.7	1.4	1.2	1.0	0.8
			Sec.	2.1	1.8	1.6	1.4	1.2	1.0	0.8	0.6	0.4	0.2	0.1
150	0.3	1.0	Prim.	4.1	3.8	3.5	3.3	3.0	2.7	2.4	2.1	1.8	1.6	1.3
			Sec.	2.6	2.3	2.0	1.8	1.5	1.2	0.9	0.7	0.5	0.3	0.1
200	0.5	1.7	Prim.	6.4	5.9	5.4	4.9	4.4	3.9	3.4	3.0	2.6	2.3	2.0
			Sec.	4.1	3.7	3.1	2.6	2.2	1.8	1.4	1.1	0.8	0.5	0.2
250	0.9	3.0	Prim.	11.3	10.4	9.5	8.6	7.7	6.8	6.0	5.2	4.4	3.6	2.8
			Sec.	6.4	5.7	5.0	4.2	3.5	2.8	2.2	1.6	1.2	0.8	0.3
300	1.7	5.6	Prim.	21.6	19.8	18.0	16.3	14.6	13.0	11.4	9.8	8.3	6.8	5.5
			Sec.	12.0	10.4	8.9	7.5	6.3	5.2	4.2	3.2	2.3	1.5	0.6

[a] For a design level of 100 mR/week. Add one tenth-value layer (TVL) for environs to reduce radiation to 10 mR/week.

[b] W = workload in ma-min/week. U = use factor. T = occupancy factor. T is equal to one for controlled areas and may be less than one for environs.

[c] These values are obtained at high filtration.

[d] Secondary barrier requirement assumes the use of a protective tube housing. (See appendix C for definition.)

TABLE 15B. *Industrial x-ray shielding requirements for controlled areas* [a] [1]

[b] *WUT*	Distance from tube to occupied area *ft*										
40,000	5	7	10	14	20	28	40				
20,000		5	7	10	14	20	28	40			
10,000			5	7	10	14	20	28	40		
5,000				5	7	10	14	20	28	40	
2,500					5	7	10	14	20	28	40
1,250						5	7	10	14	20	28
625							5	7	10	14	20
310								5	7	10	14
155									5	7	10

Potential	Approximate [c]		Type of barrier [f]	Thickness of concrete (density 147 lb/ft^3) [d], [e] *in.*										
	HVL	TVL												
kv	*in.*	*in.*												
100	0.6	2.0	Prim.	9.2	8.6	8.0	7.3	6.6	6.0	5.5	4.6	4.0	3.3	2.8
			Sec.	6.6	5.8	5.2	4.6	4.0	3.4	2.8	2.3	1.8	1.3	0.8
150	0.9	3.0	Prim.	13.3	12.4	11.5	10.6	9.7	8.9	8.1	7.2	6.5	5.8	5.1
			Sec.	9.1	8.2	7.3	6.4	5.5	4.6	3.7	2.9	2.2	1.7	1.2
200	1.1−	3.6	Prim.	16.9	15.8	14.8	13.7	12.7	11.6	10.6	9.6	8.5	7.5	6.5
			Sec.	10.6	9.6	8.6	7.6	6.6	5.6	4.6	3.7	2.9	2.1	1.4
250	1.1+	3.8	Prim.	19.3	18.0	16.8	15.6	14.4	13.2	12.0	10.8	9.6	8.4	7.2
			Sec.	12.6	11.4	10.3	9.2	8.1	7.0	6.0	5.0	4.0	3.0	2.0
300	1.2	4.0	Prim.	21.7	20.5	19.3	18.1	16.9	15.7	14.5	13.3	12.1	10.9	9.7
			Sec.	13.4	12.2	11.0	9.8	8.8	7.8	6.8	5.8	4.8	3.8	2.8

[a] For a design level of 100 mR/week. Add one tenth-value layer (TVL) for environs to reduce radiation to 10 mR/week.

[b] W = workload in ma-min/week, U = use factor, T = occupancy factor. T is equal to one for controlled areas and may be less than one for environs.

[c] These values are obtained at high filtration.

[d] For other densities, ρ, the tabular values should be multiplied by $\frac{147.}{\rho}$

[e] The indicated values for inches of concrete are for pulsating potentials; for constant potentials, 5 to 15 percent larger thicknesses of concrete may be required.

[f] Secondary barrier requirement assumes the use of a protective tube housing. (See appendix C for definition.)

TABLE 16. *Shielding requirements for 1 MV x-ray installations*

WUT[a] in mA min/week		Distance in feet from source (x-ray tube target) to occupied area										
4,000		7	10	14	20	28	40					
2,000			7	10	14	20	28	40				
1,000				7	10	14	20	28	40			
500					7	10	14	20	28	40		
250						7	10	14	20	28	40	
125							7	10	14	20	28	40
62.5								7	10	14	20	28
Type of area	Material	Primary shielding barrier thickness										
Controlled	Lead, mm [b]	130	122	114	107	99	91	84	76	68	60	52
Noncontrolled	**Lead, mm** [b]	**155**	**147**	**140**	**132**	**124**	**117**	**110**	**101**	**94**	**86**	**78**
Controlled	Concrete, in [c]	32	31	29	27	25	23	22	19.5	18	16.5	15
Noncontrolled	**Concrete, in** [c]	**38**	**36**	**35**	**33**	**31**	**29**	**28**	**26**	**24**	**22**	**21**
		Secondary shielding barrier thickness										
Controlled	Lead, mm [b]	45	36	28	21	16	10	5	2	0	0	0
Noncontrolled	**Lead, mm** [b]	**71**	**63**	**55**	**47**	**39**	**31**	**24**	**18**	**12**	**5**	**0**
Controlled	Concrete, in [c]	14.5	13.0	11.5	10.0	8.5	7.0	5.5	4.0	2.5	1.0	0
Noncontrolled	**Concrete, in** [c]	**19.5**	**18.0**	**16.5**	**15.0**	**13.5**	**12.0**	**10.5**	**9.0**	**7.5**	**6.0**	**4.5**

[a] *W*—workload in mA min/week, *U*—use factor, *T*—occupancy factor.
[b] See Table 14 for conversion of thickness in millimeters to inches or to surface density.
[c] Thickness based on concrete density of 2.35 g/cm^3 (147 lb/ft^3).
[From NCRP Report No. 34.]

TABLE 17. *Shielding requirement for 2 MV x-ray installations*

WUT[a] in mA min/week		Distance in feet from source (x-ray tube target) to occupied area										
2,000		7	10	14	20	28	40					
1,000			7	10	14	20	28	40				
500				7	10	14	20	28	40			
250					7	10	14	20	28	40		
125						7	10	14	20	28	40	
62.5							7	10	14	20	28	40
31.5								7	10	14	20	28
Type of area	Material	Primary shielding barrier thickness										
Controlled	Lead, mm [b]	237	224	211	199	186	173	160	147	134	121	108
Noncontrolled	**Lead, mm** [b]	**280**	**267**	**254**	**241**	**228**	**215**	**203**	**190**	**177**	**164**	**152**
Controlled	Concrete, in [c]	50	47	45	42	40	37	35	32	30	27.0	25
Noncontrolled	**Concrete, in** [c]	**58**	**56**	**53**	**51**	**48**	**46**	**43**	**41**	**38**	**36**	**33**
		Secondary shielding barrier thickness										
Controlled	Lead, mm [b]	67	55	44	32	20	13	8	5	2	0	0
Noncontrolled	**Lead, mm** [b]	**106**	**94**	**82**	**71**	**59**	**47**	**36**	**24**	**14**	**7**	**0**
Controlled	Concrete, in [c]	16	14	12	10	8.2	7	5	2	0	0	0
Noncontrolled	**Concrete, in** [c]	**22**	**20**	**18**	**16**	**14**	**12.5**	**10.5**	**9**	**7**	**5.5**	**3.5**

[a] *W*—workload in mA min/week, *U*—use factor, *T*—occupancy factor.
[b] See Table 14 for conversion of thickness in millimeters to inches or to surface density.
[c] Thickness based on concrete density of 2.35 g/cm^3 (147 lb/ft^3).
[From NCRP Report No. 34.]

TABLE 18. *Shielding requirements for 3 MV x-ray installations*

WUT[a] in mA min/week		Distance in feet from source (x-ray tube target) to occupied area										
2,000		7	10	14	20	28	40					
1,000			7	10	14	20	28	40				
500				7	10	14	20	28	40			
250					7	10	14	20	28	40		
125						7	10	14	20	28	40	
62.5							7	10	14	20	28	40
31.5								7	10	14	20	28
Type of area	Material	Primary shielding barrier thickness										
Controlled	Lead, mm[b]	308	294	279	265	250	235	220	205	190	175	160
Noncontrolled	**Lead, mm**[b]	**360**	**343**	328	313	298	284	**269**	254	**240**	225	**210**
Controlled	Concrete, in[c]	64	61	58	55	53	50	47	44	41	38	35
Noncontrolled	**Concrete, in**[c]	73	71	68	65	62	59	56	53	51	48	45
		Secondary shielding barrier thickness										
Controlled	Lead, mm[b]	93	78	63	48	34	22	14	9	6	3	0
Noncontrolled	**Lead, mm**[b]	143	128	113	98	83	68	53	38	23	8	**0**
Controlled	Concrete, in[c]	19.3	16.8	14.5	12.5	10.8	9.0	7.4	5.8	4.0	0	0
Noncontrolled	**Concrete, in**[c]	29	26	23	20.3	17.5	14.8	12.1	9.4	6.7	**4.0**	**0**

[a] *W*—workload in mA min/week, *U*—use factor, *T*—occupancy factor.
[b] See Table 14 for conversion of thickness in millimeters to inches or to surface density.
[c] Thickness based on concrete density of 2.35 g/cm^3 (147 lb/ft^3).
[From NCRP Report No. 34.]

TABLE 19. *Shielding requirements for 4 MV x-ray installations for controlled areas*[a]

WUT[b] in R/week at 1 meter				Distance in feet from source (x-ray tube target) to occupied area									
160,000				5	7	10	14	20	28	40	56		
80,000					5	7	10	14	20	28	40	56	
40,000						5	7	10	14	20	28	40	
20,000							5	7	10	14	20	28	40
10,000								5	7	10	14	20	28
5,000									5	7	10	14	20
2,500										5	7	10	14
		Ratios											
Type of Protective barrier	*TVL* inches of concrete	Lead to concrete	Steel to concrete	Thickness of concrete in inches[c]									
Primary	11.4	.189	.315	66.5	63.1	59.8	56.1	52.9	49.4	46.1	42.5	39.1	37.5
Secondary													
Leakage[d] 0.1%		.189	.315	32.3	28.9	25.6	21.9	18.7	15.2	11.9	8.3	4.9	1.5
Scatter													
30°	8.8			36.2	33.4	30.7	27.8	25.0	22.2	19.4	16.4	13.7	10.9
45°	7.7			30.9	28.3	25.8	23.1	20.6	17.9	15.4	12.8	10.2	7.6
60°	7.4			26.8	24.4	22.2	19.7	17.4	15.0	12.6	10.2	7.9	5.5
90°	7.0			20.9	18.8	16.6	14.6	12.5	10.4	8.3	6.1	4,1	2.0
135°	5.8			15.7	14.0	12.3	10.5	9.0	7.2	5.6	3.8	2.2	0.5

[a] For a weekly design level of 100 mR; add one tenth-value layer (*TVL*) for noncontrolled areas, to reduce to 10mR/week.
[b] $\overline{W}$—workload in R/week at 1 m, *U*—use factor, *T*—occupancy factor.
[c] Thickness based on concrete density of 2.35 g/cm^3 (147 lb/ft^3).
[d] Leakage radiation of tube housing.
[From NCRP Report No. 34.]

TABLE 20. *Shielding requirements for 6 MV x-ray installations for controlled areas* [a]

WUT[b] in R/week at 1 meter				Distance in feet from source (x-ray tube target) to occupied area									
160,000				5	7	10	14	20	28	40	56		
80,000					5	7	10	14	20	28	40	56	
40,000						5	7	10	14	20	28	40	
20,000							5	7	10	14	20	28	40
10,000								5	7	10	14	20	28
5,000									5	7	10	14	20
2.500										5	7	10	14
Type of protective barrier	*TVL* Inches of concrete	Ratios		Thickness of concrete in inches[c]									
		Lead to concrete	Steel to concrete										
Primary	13.7	.163	.292	80.0	75.9	71.8	67.7	63.6	59.5	55.3	51.2	47.0	42.9
Secondary													
Leakage[d]													
0.1%	13.7	.163	.292	38.9	34.8	30.7	26.6	22.5	18.4	14.3	10.2	6.1	2.0
Scatter													
30°	10.5			38.5	35.3	32.3	29.2	26.0	22.9	19.7	16.5	13.4	10.2
45°	9.2			28.4	25.6	22.8	20.1	17.3	14.5	11.8	9.0	6.2	3.4
60°	8.0			22.9	20.5	18.1	15.7	13.3	10.9	8.4	6.0	3.6	1.2
90°	7.0	.049	.250	18.3	16.2	14.1	12.0	9.9	7.8	5.7	3.6	1.5	0
135°	5.7			14.1	12.4	10.6	8.9	7.2	5.4	3.6	1.9	0	0

[a] For a weekly design level of 100 mR; add one tenth-value layer (*TVL*) for noncontrolled areas, to reduce to 10 mR/week.

[b] *W*—workload in R/week at 1 m, *U*—use factor, *T*—occupancy factor.

[c] Thickness based on concrete density of 2.35 g/cm^3 (147 lb/ft^3).

[d] Leakage radiation of tube housing.

[From NCRP Report No. 34.]

TABLE 21. *Shielding requirements for 10 MV x-ray installations for controlled areas* [a]

WUT[b] in R/week at 1 meter			Distance in feet from source (x-ray tube target) to occupied area									
160,000			5	7	10	14	20	28	40	56		
80,000				5	7	10	14	20	28	40	56	
40,000					5	7	10	14	20	28	40	
20,000						5	7	10	14	20	28	40
10,000							5	7	10	14	20	28
5,000								5	7	10	14	20
2,500									5	7	10	14
Type of protective barrier	*TVL* Inches of concrete	Ratio	Thickness of concrete in inches[c]									
		Lead to concrete										
Primary	15.3	.141	89.3	84.7	80.1	75.5	70.8	66.2	61.6	57.0	52.4	47.8
Secondary												
Leakage[d] 0.1%	15.3	.141	43.4	38.8	34.2	29.6	24.9	20.3	15.7	11.1	6.5	1.9

[a] For a weekly design level of 100 mR; add one tenth-value layer (*TVL*) for noncontrolled areas, to reduce to 10 mR/week.

[b] *W*—workload in R/week at 1 m, *U*—use factor, *T*—occupancy factor.

[c] Thickness based on concrete density of 2.35 g/cm^3 (147 lb/ft^3).

[d] Leakage radiation of tube housing.

Note: Based on Bly and Burrill, Symposium-Non-destructive Testing in Missile Industry, Special Technical Publication 278, American Society for Testing and Materials (1959).

[From NCRP Report No. 34.]

Appendix E. Determination of X-Ray Shielding Barrier Thicknesses

(This appendix is not a part of American National Standard N543, General Safety Standard for Installations Using Non-Medical X-Ray and Sealed Gamma Ray Sources, Energies up to 10 MeV.)

The thickness of shielding barrier necessary to reduce the exposure rate from any x-ray machine to the maximum permissible level depends upon the quality of the radiation, the quantity being produced in some chosen period of time, the distance from the tube to the occupied area, the degree and nature of the occupancy, the type of area, and the material of which the barrier is constructed. Tables 15 through 21, appendix D, give the thicknesses of lead required under a wide variety of conditions which are commonly met. Occasionally conditions may be encountered which are not covered by the tables. The necessary barrier thickness may then be computed by the use of equations 1 to 5 and the curves shown in figures 18 to 24 of this appendix.

COMPUTATION OF PRIMARY SHIELDING BARRIER THICKNESSES

By definition, primary shielding barriers protect against the radiation of the useful beam. It has been found experimentally that the transmission of x-rays through thick barriers is closely related to the peak operating potential of the x-ray tube. The filtration added to the useful beam in an x-ray machine is always small in comparison with the attenuation afforded by the barrier, and hence the barrier thickness required at a given kilovoltage is essentially independent of any changes in half-value-layer caused by added filtration in the machine. Thus, it is sufficient, for the purposes of protection calculations, to establish transmission curves specified in kilovolts under conditions of minimum added filtration. It has also been found that at any given kilovoltage and with minimum added filtration the exposure rate produced by any x-ray machine is nearly a constant when expressed in terms of roentgens per milliampere-minute at a distance of 1 m.

Figures 18 through 22 show the exposure rate measured in roentgens per milliampere-minute at a distance of 1 m from the target of the x-ray tube which would be transmitted through barriers of various thicknesses. The ordinate of the figures, given the symbol *K*, is the transmitted exposure per milliampere-minute at a reference distance of 1 m. The abscissa is the thickness of absorbing material required to give the desired value of *K*. Families of curves are shown for various kilovoltages and absorbing materials. In order to calculate the required barrier thickness for any set of parameters, it is only necessary to determine the allowed value of K and then to find the corresponding thickness on the appropriate kilovoltage curve for the barrier material which is to be used.

The value of K will depend first of all on the maximum permissible dose which is to be used. For design purposes only, this may be taken to be 100 mR/week for controlled areas and 10 mR/week for environs. Secondly, it will depend upon the workload (W), use factor (U), occupancy factor (T), and the distance (d) from the target to the area of interest. The smaller the product of WUT and the greater the distance, the larger the permitted value of K. Larger WUT values and shorter distances will result in smaller values for K.

The relation between these variables may be expressed by the equation.

$$K = \frac{Pd^2}{WUT}, \tag{1}$$

where

P = Maximum permissible dose equivalent
0.1 R/week for controlled areas
0.01 R/week for environs
d = distance in meters. (If distance in feet is used, this becomes $d/3.28$.)
W = workload in mA-min/week. (This should, insofar as possible, be averaged over a period of at least several months and preferably a year.
U = use factor.
T = occupancy factor. (See table 2 of appendix A for suggested values.)

EXAMPLE:

Find the primary shielding barrier thickness necessary to protect a controlled area 32.8 ft from the target of an x-ray machine operating at a maximum energy of 100 kVp. The wall in question has a use factor of ¼, the workload is estimated to average 1,000 mA-min/week, and the occupancy factor of the area to be protected is 1.

$P = 0.1$ R/week
$d = 32.8/3.28 = 10$
$W = 1{,}000$
$U = 1/4$
$T = 1.$

Therefore,

$$K=\frac{0.1 \times 100}{1{,}000 \times 1/4 \times 1}=0.04$$

Reference to figures 18 and 19 shows that the required barrier thickness is 0.4-mm lead or 1½ in of concrete.

Attention should be given at this point to the amount of protection which may be supplied by the structural materials of the wall. Often these appreciably attenuate the radiation and can be considered as fulfilling at least part of the barrier requirements. Unfortunately, there are few detailed attenuation data for these materials (12), but to a first approximation, their concrete equivalents[5] may be calculated on the basis of density alone. Concrete equivalent in inches is equal to the density of the material in question multiplied by the thickness of the material in inches and divided by 2.35. When these materials are of higher atomic number than concrete, this approximation tends to underestimate the concrete equivalent (i.e., the result is somewhat more shielding than is needed). Table 13 in appendix C lists some common building materials and their average densities.

For example, we may assume in the problem just given that there is already 1.0 in of sand plaster in the wall. Reference to table 13 shows that this material has an average density of 1.54 g/cm^3, making a concrete equivalent of 0.65 in already present. The remaining protection requirement of 0.85 in of concrete is shown in table 11, appendix C, to be just slightly more than 1 *HVL* for 100 kVp highly filtered radiation. Thus, the addition of 0.3 mm of lead would amply take care of the situation.

COMPUTATION OF SECONDARY SHIELDING BARRIERS

Again by definition, secondary shielding barriers are those exposed only to leakage and scattered radiation. Obviously, the use factor for these radiations is always one. Since these radiations may be of considerably different qualities, their barrier requirements must be computed separately. Furthermore, as the qualities and other factors differ greatly under various combinations of circumstances, there is no single method of computation that is always wholly satisfactory. However, *for first approximations*, the following rules may be used as guides.

LEAKAGE RADIATION. The number of *HVL*'s required in the secondary barrier for leakage radiation alone depends upon: (1) the operating potential of the tube; (2) the weekly

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[5] Concrete equivalent is defined as the thickness of concrete of density 2.35 g/cm^3 (147 lb/ft^3) affording the same attenuation, under specified conditions, as the material in question.

operating time of the tube; (3) the distance from the tube to the occupied area; (4) the nature and degree of occupancy; and (5) whether the area in question is a controlled area. The maximum amount of leakage radiation allowed through a protective tube housing is 1 R at 1 m in any 1 h. Thus, the workload is measured only in terms of the average number of hours of actual operating time per week. Table 11 in appendix C gives representative *HVL* thicknesses for lead and concrete for various kilovoltages. Table 12 gives the number of HVL's necessary to reduce the exposure rate to the required degree for various weekly operating times and various distances for both controlled areas and environs. The required barrier thickness for leakage radiation alone may be found simply by determining the number of *HVL*'s necessary to reduce the exposure rate to the permissible level for the given distance and operating time and multiplying this number by the thickness of the *HVL* of lead or concrete for the given kilovoltage. As mentioned before, if building materials other than concrete are used, the necessary thickness may be computed on the basis of their concrete equivalents.

SCATTERED RADIATION. The amount and energy of the scattered radiation depend on a large number of factors. These include the incident exposure rate, the cross-sectional area of the beam at the irradiated object, the absorption in the object, the angle of scattering and the operating potential of the x-ray tube. However, in shielding design certain simplifications can be made. For x-rays generated at potentials below 500 kV Compton scattering does not greatly degrade the photon energy and the scattering object also acts as an absorber for the lower energy photons. For design purposes the 90° scattered radiation generated from a useful beam produced at a potential of less than 500 kV, may be assumed to have the same average energy as the useful beam. Consequently, the transmission curve for the useful beam may be used in determining necessary barrier thickness. In the energy range from 0.5 to 3 MeV, the 90° scattered radiation is, to a first approximation, equal in energy distribution to x-rays generated by potentials of 500 kV regardless of the kilovoltage of the useful beam. Therefore, in this higher voltage range, the 500 kVcp transmission curve may be used in the calculation of the secondary barrier thickness. It has been shown that the amount of 90° scattered radiation is approximately 0.1 percent of that incident upon the scatterer. Thus, a *K* value 1,000 times greater may be allowed for scattered radiation than for that of the useful beam. However, the exposure rate at a fixed distance increases with the x-ray kilovoltage. Therefore, in order to use the 500 kVcp curve for the scattered radiation, *K* must be decreased by a factor of 20 for 1,000 kVcp radiation, by 120 for 2,000 kVcp, and by 300 for 3,000 kVcp.

Equation (1) may, therefore, be used for the computation of secondary barriers subject to the following modifications:

(a). For scattered radiation from useful beams generated at 500 kVcp or below,

$$K=\frac{1{,}000\times P\times d^2}{WT} \text{ (Use curve for kV of useful beam).} \qquad (2)^6$$

(b). For scattered radiation from useful beams generated at 1,000 kVcp,

$$K=\frac{1{,}000\times P\times d^2}{20\ WT} \text{ (Use 500 kVcp curve).} \qquad (3)^7$$

(c). For scattered radiation from useful beams generated at 2,000 kVcp,

$$K=\frac{1{,}000\times P\times d^2}{120\ WT} \text{ (Use 500 kVcp curve).} \qquad (4)^7$$

(d) For scattered radiation from useful beams generated at 3,000 kVcp,

$$K=\frac{1{,}000\times P\times d^2}{300\ WT} \text{ (Use 500 kVcp curve).} \qquad (5)^7$$

If the barrier thicknesses for leakage and scattered radiations are found to be approximately the same, 1 *HVL* should be added to the larger one to obtain the required total secondary barrier thickness. If the two differ by a large enough factor (this situation is assumed to exist if there is a difference of at least 3 *HVL*'s), the thicker of the two will be adequate.

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[6] If a 50-cm target-object distance is used, divide *K* by 4.

[7] If a 70-cm target-object distance is used, divide by 2.

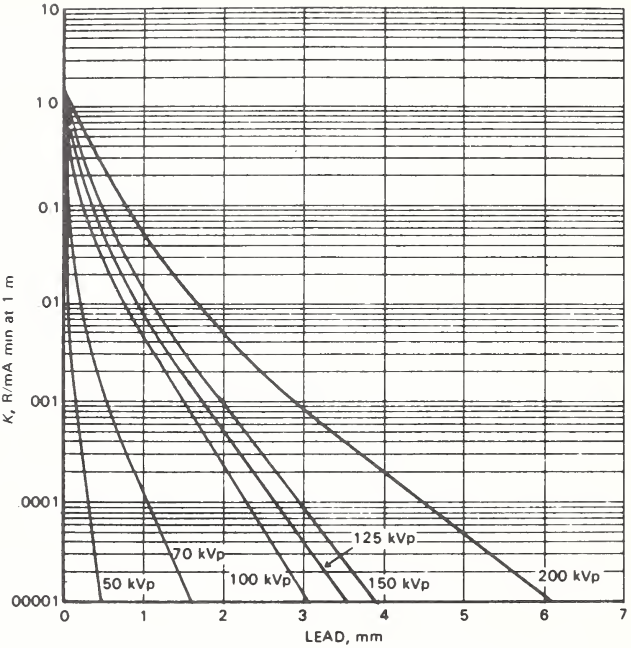

FIGURE 18. *Attenuation in lead of x rays produced by potentials of 50- to 200-kV peak.*

The measurements were made with a 90° angle between the electron beam and the axis of the x-ray beam and with a pulsed waveform. The curves at 50 and 70 kVp were obtained by interpolation and extrapolation of available data. The filtrations were 0.5 mm of aluminum for 50, 70, 100, and 125 kVp, and 3 mm of aluminum for 150 and 200 kVp [2].

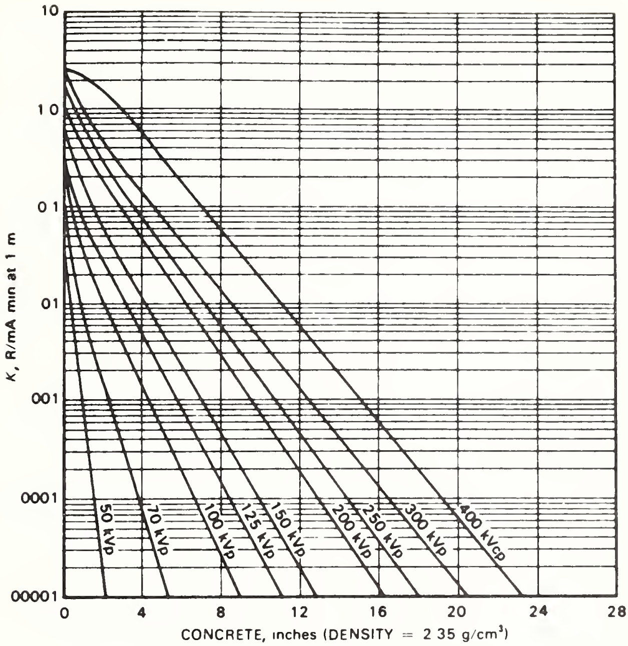

FIGURE 19. *Attenuation in concrete of x rays produced by potentials of 50 to 400 kV.*

The measurements were made with a 90° angle between the electron beam and the axis of the x-ray beam. The curves for 50 to 300 kVp are for a pulsed waveform. The filtrations were 1 mm of aluminum for 70 kVp, 2 mm of aluminum for 100 kVp, and 3 mm of aluminum for 125 to 300 kVp (Trout et al., 1959) [11]. The 400-kVcp curve was interpolated from data obtained with a constant potential generator and inherent filtration of approximately 3 mm of copper (Miller and Kennedy, 1955) [8] [2].

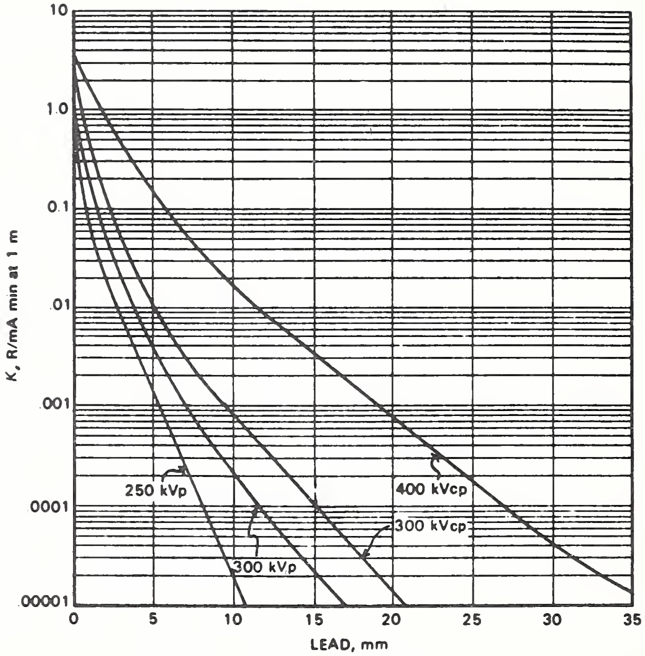

FIGURE 20. *Attenuation in lead of x rays produced by potentials of 250 to 400 kV.*

The measurements were made with a 90° angle between the electron beam and the axis of the x-ray beam. The 250-kVp curve is for a pulsed waveform and a filtration of 3 mm of aluminum. The 400-kVcp curve was obtained with a constant potential generator and inherent filtration of approximately 3 mm of copper (Miller and Kennedy, 1955) [8]. The 300-kVp curve is for pulsed waveform and 3 mm of aluminum (Trout et al., 1959) [11] [2].

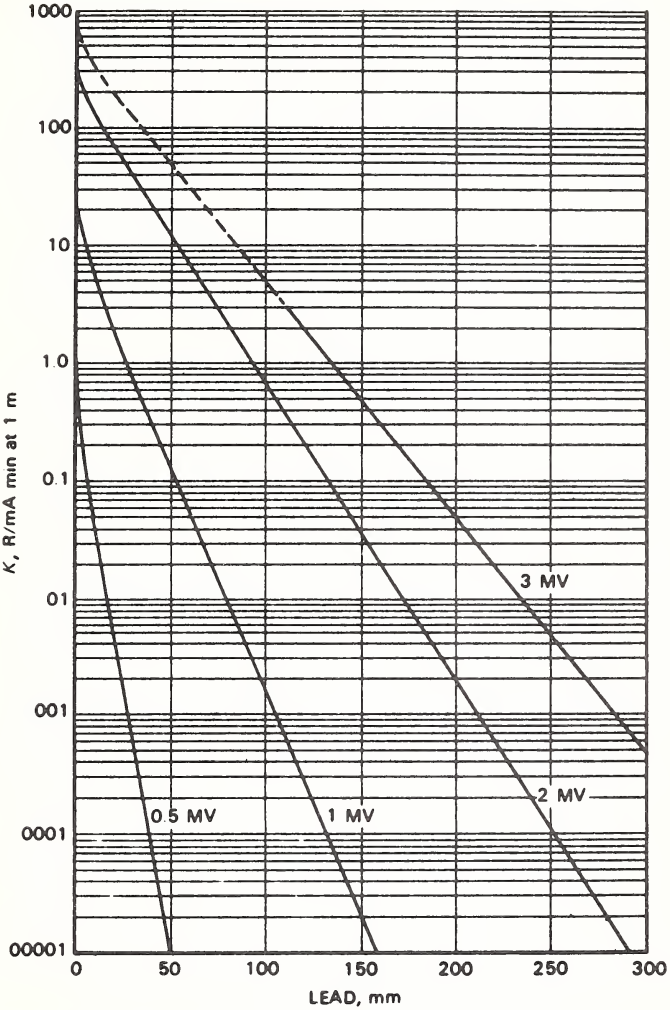

FIGURE 21. *Attenuation in lead of x rays produced by potentials of 0.5 to 3 MV constant potential.*

The measurements were made with a 0° angle between the electron beam and the axis of the x-ray beam with a constant potential generator. The 0.5 and 1 MV curves were obtained with filtration of 2.88 mm of tungsten, 2.8 mm of copper, 2.1 mm of brass, and 18.7 mm of water (Wyckoff et al., [13]). The 2 MV curve was obtained by extrapolating to broad-beam conditions (E. E. Smith) the data of Evans et al., [3]. The inherent filtration was equivalent to 6.8 mm of lead. The 3 MV curve has been obtained by interpolation of the 2 MV curve given herein, and the data of Miller and Kennedy [9].

[Data courtesy of the authors, Radiation Research, Radiology and Academic Press.]

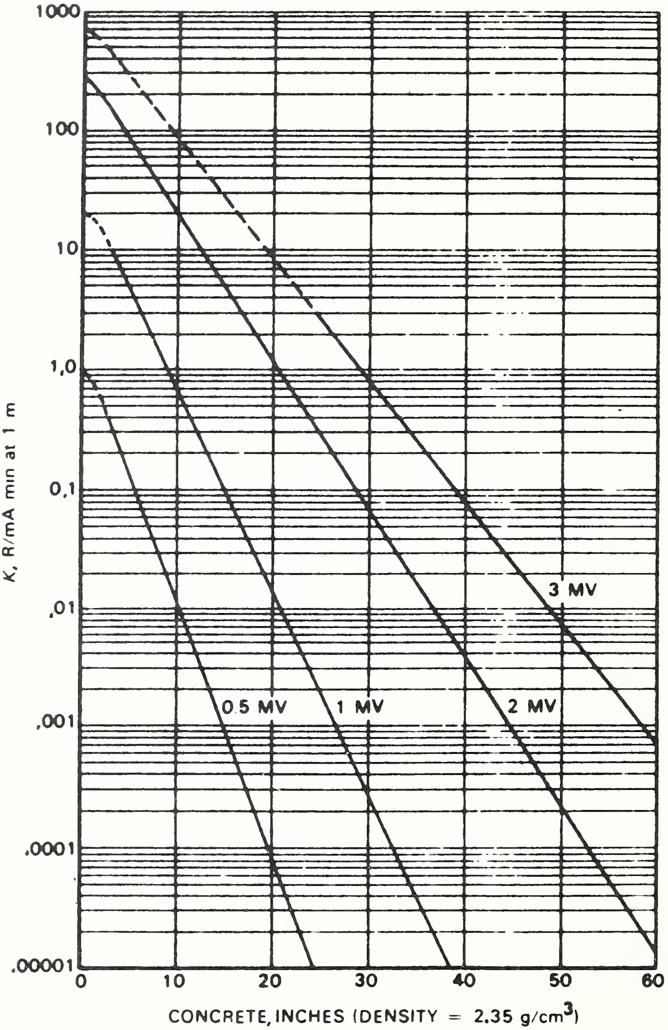

FIGURE 22. *Attenuation in concrete of x rays produced by potentials of 0.5 to 3 MV constant potential.*

The measurements were made with a 0° angle between the electron beam and the axis of the x-ray beam and with a constant potential generator. The 0.5 and 1 MV curves were obtaind with filtration of 2.8 mm of copper, 2.1 mm of brass, and 18.7 mm of water (Wyckoff et al. [13]). [Data courtesy of the authors and Radiology.] The 2 MV curve was obtained by extrapolating to broadbeam conditions (E. E. Smith) the data of Evans et al. [3]. The inherent filtration was equivalent to 6.8 mm of lead. [Data courtesy of the authors and Radiology.] The 3 MV curve has been obtained by interpolation of the 2 MV curve given herein, and the data of Kirn and Kennedy [5]. [From "Betatron X Rays: How Much Concrete for Shielding" by F. S. Kirn and R. J. Kennedy. Copyright 1954, McGraw-Hill Book Company, New York. Used with permission of the McGraw-Hill Book Company.]

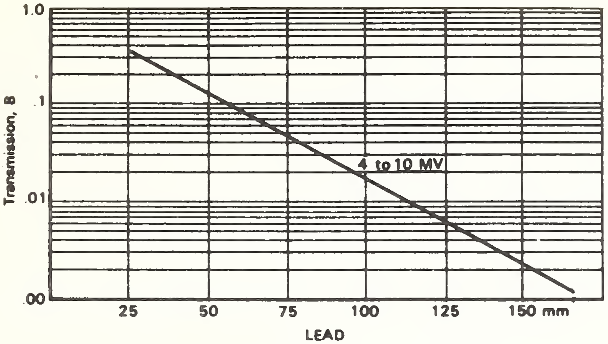

FIGURE 23. *Attenuation in lead of x rays produced at 4 to 10 MV based on Karzmark and Capone* [*6*], *and Miller and Kennedy* [*9*].

[Data courtesy of the authors, The British Journal of Radiology, Radiation Research and Academic Press.]

[From NCRP Report No. 34.]

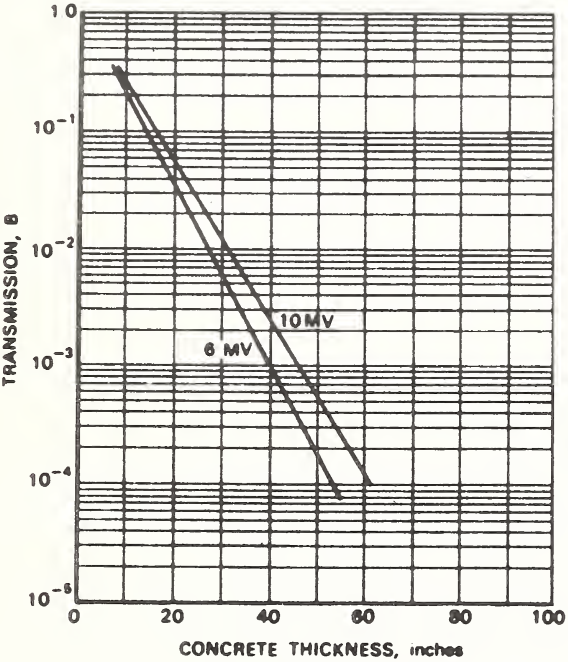

FIGURE 24. *Attenuation in concrete (density 147 lb/ft*^{3}*) of x rays produced at 6 and 10 MV (Kirn and Kennedy* [*5*]).

[From "Betatron X Rays: How Much Concrete for Shielding" by F. S. Kirn and R. J. Kennedy. Copyright 1954, McGraw-Hill Book Company, New York. Used with permission of McGraw-Hill Book Company.]
[From NCRP Report No. 34.]

Appendix F. References

(This appendix is not a part of American National Standard N543, General Safety Standard for Installations Using Non-Medical X-Ray and Sealed Gamma Ray Sources, Energies up to 10 MeV.)

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ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This standard establishes requirements for the design and operation of common types of installations which use gamma and x radiation for non-medical purposes. Its objective is to protect persons who work with or are near such installations, as well as the general public, against, excessive exposure to radiation. Maximum permissible dose limits established by the National Council on Radiation Protection and Measurements are cited. Methods for achieving adequate radiation protection are described, including structural details, surveys and inspections, and operating procedures. Appendixes contain technical information useful for design of radiation shielding barriers.

KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Gamma-ray equipment; radiation installations; radiation safety; x-ray equipment.

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